REVIEW ARTICLE

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Extending the Life of Ammonia Refrigeration Systems: Part I

by
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BACKGROUND

This article is based on a paper presented at an IIR conference, Ammonia Refrigeration Technology for Today and Tomorrow, held in Ohrid, Macedonia, on April 19-21, 2007. It addresses issues related to the useful working life of ammonia refrigeration equipment. It considers the economic case for extending the life of equipment and reviews the factors which affect the condition of equipment. Key issues in the design, operation and maintenance of plants are explained, with examples to illustrate the effect of earlier decisions on later life. Some recommendations are given as guides to good practice when equipment is being modified or reconfigured, with the objective of finding ways in which existing systems can be brought into line with current international safety standards without incurring an excessive investment cost.

Part II will deal with operating issues, maintenance priorities, modification of existing systems, recommendations and conclusions.

I. INTRODUCTION

Industrial refrigeration systems use rugged design and construction, and provide decades of useful service if they are properly used and correctly maintained. This article reviews system design for long life and suggests key steps to be followed in operation and maintenance. This is particularly relevant to equipment in use in Eastern Europe, Russia and the former Soviet Union states and the developing world. Much of the old refrigeration plant in these countries uses ammonia as the refrigerant, but some of the equipment is in poor condition, and owners are tending to replace this aged estate with fluorocarbon equipment because it is perceived to require less maintenance and therefore to be easier to operate. This is potentially an expensive mistake because the true cost of ownership is dominated by the energy cost required to operate the equipment. Ammonia has always been particularly good in this respect, and has retained its position as the preferred refrigerant for industrial systems in the United States, Canada, Australia and most of Europe.

II. ECONOMIC CASE

II.1. Cost of ownership

To have a clear idea of the total cost of owning and operating a refrigeration system it is necessary to consider all relevant expenditure including capital purchase, cost of maintaining in reasonable working order, cost of repairing when it suffers a breakdown, cost of electricity for the system and associated devices and other utility costs, such as the cost of water for an evaporative condenser. Finally, if the business is being treated as a going concern, it is necessary to consider the cost of ultimate replacement at the end of its useful life. It is important to emphasize that most of these costs are fictitious: they have not yet happened, and the analysis is wholly dependent on a reasonable guess of what these costs might be. To create a balanced picture it is also necessary to weight future expenditure by various factors to allow for the effect of inflation on the cost of energy and materials, or to allow for the effect of bank interest rates on the cost of borrowing money. This is often done by converting future expenditure into a "net present value". This can be thought of as the amount of money that would need to be set aside now to cover the cost of expenditure in future. Variations in the assumptions made about inflation and interest rates will shift the balance between current investment and future benefits. In addition, to make the analysis even less precise, the performance of the equipment is usually heavily weather-dependent, and often is also affected by the load profile imposed on the plant. So in order to make an assessment of the total cost of ownership it is necessary to make educated guesses about the level of maintenance required, the number of breakdowns that will occur, the lifespan of the equipment, the cost of labour, energy and water, the inflation rate, the cost of borrowing money, the production schedule for the plant and even the weather forecast. It is of course impossible to do this accurately; fortunately what is important in this analysis is the comparison between net present values for different options, so the guesses only need to be consistent with each other and across all the options considered.

II.2. Examples

To calculate the net present value of expenditure the costs are divided into two categories. Those that occur infrequently in the life of the plant, for example replacement of major parts of the system, or major overhaul costs can be calculated from the formula, shown in *Equation 1*.

Occasional costs:

$$PV = (1 + i)^{-n} \qquad (1)$$

Those that recur regularly, for example energy, water and maintenance costs can be calculated from the formula shown in *Equation 2*.

Recurring costs:

$$PV = \frac{1 - (1 + i)^{-n}}{i} \qquad (2)$$

where n is the number of years the system will last (or number of years to an occasional event) and i is the annual index of price inflation and the cost of borrowing. For low inflation rates this can be approximated by the cost of borrowing minus the inflation rate. For example, if inflation is 3% and the bank rate is 5%, then the index would be 2%.

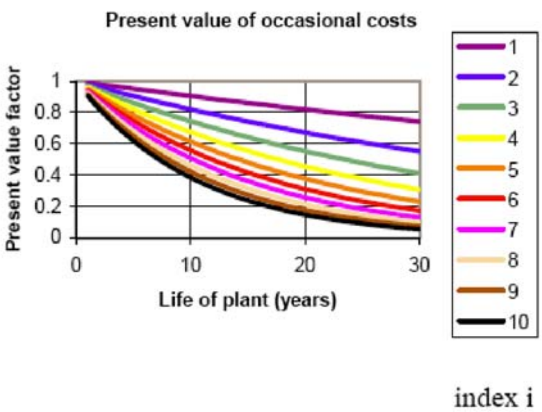

Figure 1. PV for occasional costs

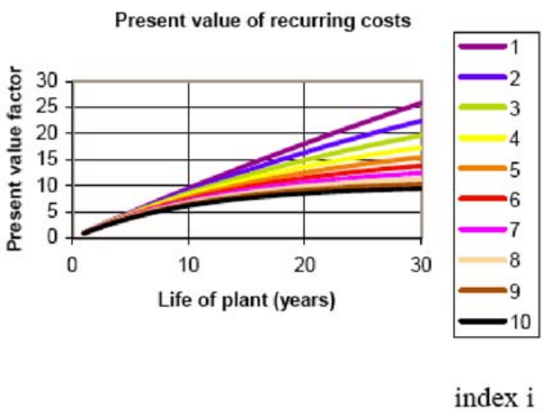

Figure 2. PV for recurring costs

Consider a screw compressor which has worn tip seals, causing a reduction in annual average COP from 3.2 to 2.4. If the original compressor capacity was 500 kW, the system runs for 3000 hours per year, the current cost of replacement is 75 000 € and the cost of electricity is 0.08 € per kWh, then the following calculation can be made for evaluating the cost of replacing the compressor now or waiting 5 years until the end of life of the plant, assuming that the annual index is 3%.

Case A: The cost of running the compressor for a year with the reduced COP is:

$$\frac{500}{2.4} \times 3000 \times 0.08 = 50\,000 \text{ €}$$

The recurring NPV factor for an index of 3% for 5 years is 4.58 so the net present value of the energy cost is 229 000 €. The occasional NPV factor for the cost of replacement in 5 years' time is 0.863, so the net present value of the repair is 64 725 €.

Case B: The cost of running the new compressor for a year at the design COP is:

$$\frac{500}{3.2} \times 3000 \times 0.08 = 37\,500\ €$$

Using the same NPV factor, the net present value of the energy cost is 171 750 €.

Thus the total cost of ownership of running the old compressor is 293 725 €, whereas the cost of ownership of replacing the compressor for the remaining 5 years of the plant life is
246 750 €; 84% of the cost of running the inefficient machine.

If the annual index is 6%, then the recurring NPV factor is 4.21 and the occasional NPV factor is 0.747. These values give costs of ownership of 266 525 € and 232 875 € for running the old and the new compressors respectively. The cost of replacement is still 13% cheaper.

This method of analysis can also be applied over the whole life of the plant to compare the cost of ownership for different design options. In this case, where a cost occurs several times in the life of the plant such as replacement of an air-cooled condenser after 5 years and 10 years in the 15-year life of the plant, the recurring calculation should be applied once for each event, using the time from the present to the event as the life n. For an index of 3% and an event occurring every 5 years the NPV factor would be 0.863 for the first event and 0.744 for the second. Thus a combined factor of 1.607 accounts for both events. If the plant is to be considered to be a "going concern" at the end of its life then it may be appropriate to consider full system replacement as an occasional cost, but as the cost of energy, water and maintenance over the life of the system is usually so much higher than the capital cost this refinement is unlikely to affect the conclusion of the comparison exercise.

III. FACTORS AFFECTING SYSTEM LIFE

III.1. Components wear out

The most obvious reason for a system reaching the end of its useful life is that the moving parts wear out. Compressors wear even if treated carefully, and any machine with over 50 000 hours run will benefit from replacement of moving parts. However, in screw compressors where the compression effectiveness is dependent on the tip seals, the efficiency will be greatly reduced long before the machine is completely worn out. The condition of the lubricating oil is the key factor in minimizing rotor wear. Dirty oil will introduce particles into the compressor which accelerate the wear process. If the oil viscosity is too low, then the hydrodynamic bearings allow too much shaft movement. This may cause pick-up in the bearings, increasing the amount of white metal debris from the bearings themselves, or it may allow contact between the rotor and the compressor casing, which will also wear the tips and produce more abrasive particles. Once wear starts, it accelerates as more metal particles circulate, so it is important to ensure that the oil condition is correct. As the oil is worked through the system the viscosity may increase, which ultimately can also lead to lack of bearing lubrication. Liquid carried to the screw compressor suction can cause a temporary contact between rotor and casing or between shaft and bearing journal, causing metal fragments to be worn off and enter the oil. It is important to set a high standard for system cleanliness and plant operation, and not to accept undesirable events such as liquid carryover. Slide valve pistons also wear, but usually it is possible to change seals relatively easily. The slide valve of a screw compressor is always subject to unbalanced forces because the suction pressure acts on one end of the slide and the discharge acts on the other. If the piston seal is leaking, then the slide will tend to creep towards full load when the compressor is supposed to be maintaining part-load condition.

Smaller components also wear out. A solenoid valve operating once per minute performs over 5 million cycles in 10 years. This is sufficient even in a clean system to wear the side of the armature in an indirect-acting (pilot operated) valve. It will then not seal on the pilot orifice and the valve will not maintain a liquid seal. This minor issue could lead to significant damage, for example liquid hammer in a hot gas defrost system. Pumps and fans may also suffer expensive damage as the result of the failure of a small component. If a fuse blows on a fan peripheral heater in a cold store, ice build-up may shatter fan blades when the fan starts after a defrost.

III.2. Components corrode

The most obvious victims of corrosion in low-temperature ammonia systems are the pipework and pressure vessels. Parts of the system which are alternately hot and cold, particularly where ice is regularly freezing and thawing, are particularly susceptible to corrosion. Cold surfaces will always tend to attract moisture from the surrounding air, so all insulation must be protected by a suitable covering called a vapour barrier. This requirement is not necessary for insulated hot pipes, so it is often not well understood, but if the insulation is not covered by a completely vapour-tight seal it will quickly become saturated with water and will then freeze, destroying its insulating properties. Ice forms its own vapour barrier, so pipework under a permanent ball of ice is likely to remain in good condition, but the ice will build up until the surface temperature is 0°C, at which point it will be wet. The pipework at the edge area of an iceball like this is particularly prone to corrosion.

The condenser is also likely to corrode. For larger systems these may be evaporative condensers which contain a zinc-coated pipegrid. These can give years of service in the right conditions, but once the zinc protection has been compromised, the steel coil corrodes and leaks. If the model of condenser is still produced, then it is often possible, subject to suitable access for cranes, to replace just the coil. Air-cooled condensers, particularly with aluminium fins, can also be subject to severe corrosion, particularly in salty environments. This is a case where it is better to spend money on a replacement condenser sooner rather than later because the system efficiency will be significantly impaired if the condenser fins are badly corroded, and the cost of the new condenser will quickly be recovered in reduced energy bills if the plant is quite heavily loaded. It is also worth paying for corrosion resistant coating to the fins in order to prevent a repeat occurrence within a few years.

Evaporator coils are usually less subject to corrosion because they are normally in a less harsh environment and they operate at lower temperatures. Occasionally, the evaporator may be attacked by chemicals in the air. Cases are reported of severe corrosion, particularly of aluminium and steel in vegetable and salad washing facilities (from chemicals in the wash water), in bakeries and bread factories (from yeasts in the dough) and in spice factories. Galvanized coils are generally the most corrosion resistant, but particular care must be taken if the facility uses potassium formate or potassium acetate as a secondary coolant, as these fluids are particularly aggressive to zinc.

III.3. System blockages

A system which has run for many years, particularly at low temperature and using mineral oil, will tend to clog on the low-temperature side of the plant with decomposed oil, water, dirt and silt. This is most likely to affect the evaporators, where the inner surfaces will be fouled with this mixture, causing severe degradation of the heat transfer performance.

III.4. Infrastructure decays

In addition to corrosion of the pipework and vessels, consideration should be given to the condition of the infrastructure. This includes the building fabric (roofs, walls and floors), support steelwork for the pipework, and the condition of the electrical cabling on the plant. If the machinery room is no longer weathertight, then the mechanical condition of all equipment is likely to be impaired. Electric motors are also more susceptible to damage if the ambient temperature is not maintained within moderate limits. Pipe supports that are damaged and permit excessive pipe movement can apply excess loads to vessels or compressor sets, and this can cause premature failure of equipment.

III.5. Requirements change

Often, the main reason for scrapping a plant is not that it reached the absolute end of its life, but that the requirements for the cooling process changed beyond the point where the old plant could cope. This could be a significant increase (or even reduction) in capacity, a major shift (up or down) of operating temperature or perhaps a change of process type. For example shifting from blast freezers with off-cycle defrost to plate freezers would be difficult, even if the operating temperature and heat load remained the same. The liquid pump rate would need to be significantly increased, and there would be a requirement for hot gas defrosting, in order to release the frozen blocks from the plate freezer at the end of the cycle. It might be possible to retain the compressors and condensers from the old plant, but the surge drum and low side pipework would require extensive modification.

III.6. Obsolescence

Some components may reach the point where they are no longer in production and it becomes increasingly difficult to source spare parts for them. The original manufacturer may no longer be in business, or the company may have changed hands, so often that the manufacturing details are not available. In this situation, older equipment is often easier to maintain in working order than newer, more sophisticated machinery. Compressors are the most obvious example of this effect, but it also applies to liquid pumps, oil pumps and particularly to electrical and electronic components. When components are no longer available, it may be possible to have spare parts manufactured either to original manufacturer's drawings, if they are available, or as a copy of the original part. This is likely to introduce additional unreliability however, because even if the parts are dimensionally accurate there will probably be differences in material specification or production method which could alter the performance of the replacement component or shorten its life. As equipment gets older and parts become more difficult to source, the site engineer should identify key spares and ensure that they are available by carrying a site stock of parts or making arrangements for fabrication before the need arises. If the need arises to use these parts, the time spent in planning will be well rewarded through minimal downtime and lower cost of replacement. The list of critical spares should be reviewed regularly, preferably at least on an annual basis. If the number of critical spare parts on a single component becomes excessive, consideration can also be given to investment in a new component without replacing the complete system.

IV. DESIGN CONSIDERATIONS

This section of the article examines some elements that should be considered when a new system is designed in order to ensure that the life of the equipment is extended as much as possible. In many cases where provisions for future extension, modification or even just maintenance of equipment are incorporated at the planning stage of a project the cost is negligible. For example, positioning shell-and-tube condensers so that there is sufficient space for tube cleaning or for tube withdrawal and replacement may not cost anything at the planning stage, but could make future maintenance significantly cheaper and easier. A less obvious consideration is the provision of access around key components for their maintenance or replacement. Often, in modern equipment there is a tendency to build everything into a single packaged unit for transport to site. Restrictions for road traffic as well as plant room space can sometimes impose significant constraints on package size, making future access very difficult. Even on these packages, the designer should ensure that every major component and pressure vessel can be removed without completely dismantling the package.

IV.1. Central plant or modular

In principle, the construction of a central plant system provides maximum scope for rearrangement and the replacement of individual components, but there is also a risk that the central system will suffer a catastrophic failure that will require complete system replacement. If a design for modular equipment is planned carefully, it will provide scope for more significant maintenance and refurbishment work without completely disrupting the operation of the refrigerating system. For example, it would be possible in a large cold store system with four independent refrigerating modules to replace the suction pipework of any one of them without adversely affecting the performance of the system as a whole, provided the work had been planned well in advance to coincide with lower heat loads. This might be done over a holiday period, or at weekends when store traffic is less, or it could be done in winter months when ambient temperatures are lower.

IV.2. System configuration

The designer must strike a balance between maximizing the flexibility of the system and increasing its complexity to the point where the plant operators will not be able to understand it. This will lead to inefficient operation and possibly also to expensive breakdowns. There is great benefit in arranging the compressors in a two-stage plant to be connected through appropriate isolating valves to two suction temperature levels. This helps to accommodate changes in load as factory production is changed, and if the compressors and pipework in the plant room are well laid out then the necessary valve arrangement will be simple, easy to operate and impossible to get wrong.

The heat loads in the factory must also be grouped carefully to minimize complexity, while still making the system as efficient and reliable as possible. It is reasonable to include a small load at slightly higher temperature onto a baseload, for example to feed a 50 kW chilled water circuit from a 500 kW chilled glycol system, but if the heat loads were reversed, the energy penalty in running a large chilled water system at low temperature would be excessive. The same principle applies to cold storage and freezer systems. A small cold store load can reasonably be attached to a large freezer plant without an excessive energy penalty; however, in this case the cold store must be capable of running when the freezer is not in use, for example overnight or at weekends. In this case it might be appropriate to add a small compressor to the freezer plant to handle the light duty. It may also be possible to arrange alternative suction pressure set points, so that the pressure is allowed to cycle through a much wider range when the freezer is not operating. In this arrangement, the large freezer compressor would pull the suction pressure down to a low limit and then switch off. As liquid continues to be pumped to the cold store the pressure in the suction side would slowly rise until it reached an upper limit, typically well above the level required for freezing, but still capable of cooling the cold store. Typical values for these suction conditions might be a saturated suction temperature of –43°C during freezer operations with a band of cold store saturated suction temperatures ranging from –38°C to –32°C in order to maintain –25°C in the cold store. At the end of a freezing operation, the compressor would switch off but the liquid pumps would continue to run. The surge drum pressure would initially be –43°C and would gradually rise, probably over a period of many hours. When the saturated suction temperature reaches –32°C the compressor would start and draw vapour from the surge drum until the saturated temperature reaches –38°C. It would then switch off until the pressure rises again. The temperature range for this type of operation should be wide enough to avoid short-cycling. The range is dependent on the relative size of the cold store load compared to the total plant capacity, the volume of the total low-pressure part of the system and the arrangement of the compressors. The compressor when running should be loaded as high as possible, although it may not be feasible to run at 100%.

There is a tendency in plant design to include as many crossover connections as possible to give increased flexibility. If the designer does not include these connections the plant operator will probably add them at the earliest opportunity. Where this practice increases complexity to the point that the system's efficient and reliable operation is compromised, it should be discouraged. Where liquid transfer and pumpout lines are permanently connected and the shut off valve fails to seal tightly, there is the possibility of gas leaking into the suction of the compressor and reducing the efficiency, or of liquid leaking into a vessel and filling it beyond its normal operating limits.

IV.3. Design for reliable operation

The designer, in addition to arranging the equipment to perform its normal function, must also consider the consequences in his design of abnormal events. For example, the system should be able to cope with operating with too much refrigerant in the system, or with too little, and if these situations are extended to the extreme, the system must raise an alarm and shut down safely without damaging any equipment. The design should allow for any part to be pumped out with minimum difficulty, and it should be possible to isolate every shut off valve for maintenance and repair; however, great care must be taken, particularly in liquid lines, to ensure that liquid cannot be trapped between two closed valves. In a typical pumped circulation system with a high-pressure receiver it should be possible to transfer all the refrigerant either to the high-pressure receiver or to the surge drum, enabling work to be done on any part of the system without decanting refrigerant. The most difficult valves to accommodate in this way are pump suction valves, evaporator isolating valves, condenser outlet valves and the "king valve" – the shut-off valve in the main liquid line from the high-pressure receiver. In these cases it will probably be necessary to shut down the system to service these valves. This is where a modular plant provides a significant advantage, because cooling to the process or store will not be completely removed during this maintenance activity.

The system should be configured to prevent liquid from reaching the compressor suction, by placing a sufficiently large accumulator, surge drum or knock-out pot in the suction line from the evaporators. In pumped circulation and direct-expansion systems, this vessel should be fitted with a high-level switch wired to signal an alarm condition and stop compressors when the liquid in the vessel reaches the upper limit. A further advantage of modular equipment is that if the system is "critically charged" then there will not be sufficient refrigerant charge to fill the suction vessel, so a high-level alarm is not necessary. It is also possible to include a low discharge temperature alarm in the control software for modern systems so that liquid carryover is identified quickly. This will not be sufficient to protect a reciprocating compressor from a slug of liquid in the suction, but it would help to prevent premature bearing wear in a screw compressor.

The designer must also consider what happens before, during and after evaporator defrosting to ensure long-term system reliability. Often, in hot gas defrost systems the plant will initially work extremely well, but as components wear or are adjusted on site, the defrost becomes less and less effective, or system malfunctions can cause dangerous occurrences. The hot gas header should not be pressurized except when a defrost is occurring: to achieve this, it is necessary to use a suction shut-off valve which closes when pressurized. The hot gas header should have a liquid drain point connected to the wet return pipe, with a liquid level switch. The float switch should be monitored by the control system, as regular release of liquid from the header would indicate that the hot gas solenoid valve was leaking. If uncorrected, this could cause liquid hammer, resulting in significant damage to other valves, and possibly also fracturing the pipework with the resultant sudden release of a lot of ammonia. The liquid trap in the hot gas header can easily be retrofitted to existing systems, although changing the type of suction shut-off valve is a more difficult job.

IV.4. Protect equipment from external damage

The designer must consider the possibility of external damage when positioning refrigeration equipment. Delicate pipework, for example gauge connections, should not be located where it can be stood on. Valve spindles should not extend beyond the line of a package into walkways or corridors where they may be struck by passing vehicles or pedestrians. Evaporators should be provided with protective steelwork where they may be hit by fork trucks. Equipment located at ground level outside, for example evaporative condensers or high-pressure receivers should be protected from traffic damage, using heavy concrete barriers if necessary.

Where insulated pipework runs through roof voids or across roofs outside and there is a requirement for pedestrian access then suitable protection in the form of metallic cladding should be fitted and suitable access bridges should be provided. If there is a need to access equipment above the pipes, then permanent steps should be fixed in place at a suitable point so that the technician does not need to stand on or walk on the insulated pipework. It is even better if the designer arranges the equipment to avoid the need for maintenance access above insulated equipment.