AIR CONDITIONING AND REFRIGERATION
Journal
The magazine of the Indian Society of Heating, Refrigerating and Air Conditioning Engineers

Issue : July-September 2001

New Developments in Industrial Refrigeration

By Andy Pearson

*Andy Pearson is the managing director of Star Refrigeration's Contracts group, Glasgow, Scotland (**apearson@star-ref.co.uk**).*

Carbon dioxide is one of the earliest substances to have been used as a refrigerant. In the mid-19th century, when refrigeration technology was in its infancy, technicians used readily available substances, such as ether, sulphur dioxide, air, ammonia and carbon dioxide. Each substance had its advantages and disadvantages, and as compressor technology developed, ammonia came to dominate the early refrigeration market.

The recent swing away from chlorine based synthetic refrigerants has renewed interest in these early substances, and particularly in carbon dioxide, which provides exceptionally high refrigeration capacities, is relatively benign and is easy to work with. As a result, carbon dioxide is being used in applications ranging from domestic heat pumps through car and bus air-conditioning to large-scale, low-temperature industrial refrigeration.

The use of carbon dioxide instead of ammonia in food factories is attractive for several reasons, but it is not without drawbacks. The most obvious advantage is that carbon dioxide is non-flammable. It is even possible to imagine a system where the carbon dioxide charge is used as an extinguisher to assist firefighters.

Toxicity is a more complex subject. Although carbon dioxide is not acutely toxic, unlike ammonia, it must nevertheless be treated with respect owing to its unusual toxicology. Other advantages are more dependent on site conditions, but it is possible that the installation cost, running cost and maintenance cost can all be reduced in comparison with a large distributed ammonia plant, and certainly in comparison with a large R-404A plant.

Some of the recent development work has been conducted in Glasgow, Scotland. Glasgow was the home of James Watt, William Rankine and Lord Kelvin who all worked on the science of thermodynamics in its early years. Their names are still associated with various units and cycles in this respect, so this connection is quite appropriate. In 1992, a Glasgow industrial refrigeration contractor designed and installed the first supermarket refrigeration system using carbon dioxide as a volatile secondary refrigerant in cascade with an ammonia plant. More recently, the company has engineered a carbon dioxide compressor system as part of a large food factory refurbishment. This project included the construction of a demonstration unit to prove the concept before the main project proceeded.[1]

The demonstration unit included a screw compressor, plate condenser, surge drum and hermetic pump to deliver carbon dioxide to a single air cooler installed in a low-temperature cold chamber. The plant was designed to extract 100 kW (28.5 ton) at an air temperature of –48°C (–54°F). The compressor swept volume is 100m^3/h (59 cfm) at 3,000 rpm. Heat is rejected to the existing R-22 plant at intermediate temperature. The demonstration plant was installed in November 1998, and has been in continuous use since then, with only minor modifications. The main project, based upon successful commissioning of the demonstration plant, was the replacement of the complete R-22 system. A phased program was developed so that production would continue without interruption throughout the project. The heat load is more than 20 times greater than the demonstration unit, and comprises air coolers for the cold room and process evaporators that may be required to operate at a slightly higher pressure.

The carbon dioxide system was divided into three sections. Each was served by a surge drum and pump set. Two sections serve banks of process evaporators and the third feeds the air coolers. It was a requirement of the project that the system must be designed for a long life with minimal risk of plant failure. The cooling equipment is built into the structure of a 60-year-old "listed" building. Extended downtime would result not only in costly loss of production, but also could pose a threat to the fabric of the building if the cold room were allowed to warm up from –40°C (–40°F) towards ambient. Two key design decisions followed from the risk minimization requirement. The first was to use oil-free compressors on the carbon dioxide circuit and the second was to make the design pressure for both systems 28 Bar(G) (412 psig).

Ammonia systems are suited to use in food factories for low-temperature freezing and storage applications, but with the disadvantages of acute toxicity and relatively large swept volume requirements at low temperatures. The problem of toxicity is present in all ammonia systems, and safe systems of operation, including the provision of alarm systems and the rehearsal of emergency procedures have been developed to ensure that risk is minimized.

The issues surrounding swept volume requirements are less clear cut. It is possible to engineer ammonia plant for operation down to –60°C(–76°F), but anything below –35°C (–31°F) requires relatively large compressors because the gas density is so low. In addition, evaporation below atmospheric pressure tends to allow air to leak into the system causing inefficiency in the short term and unreliability in the long term. It is therefore clear that for evaporation below –35°C(–31°F) there are advantages in selecting a relatively non-toxic, dense gas with a high pressure-temperature characteristic.

Carbon dioxide is the only common, "natural" refrigerant that meets these requirements. The triple point for carbon dioxide is relatively high, at –56.6°C (–69.9°F) and 4.18 Bar (G) (61.5 psig). At this point gas, liquid and solid can all co-exist, and taking a vessel of saturated liquid down to this pressure will cause solid particles to form in the liquid. To enable reliable plant operation in a pumped liquid system, it is necessary to keep the carbon dioxide temperature above –55°C (–67°F) under all circumstances.

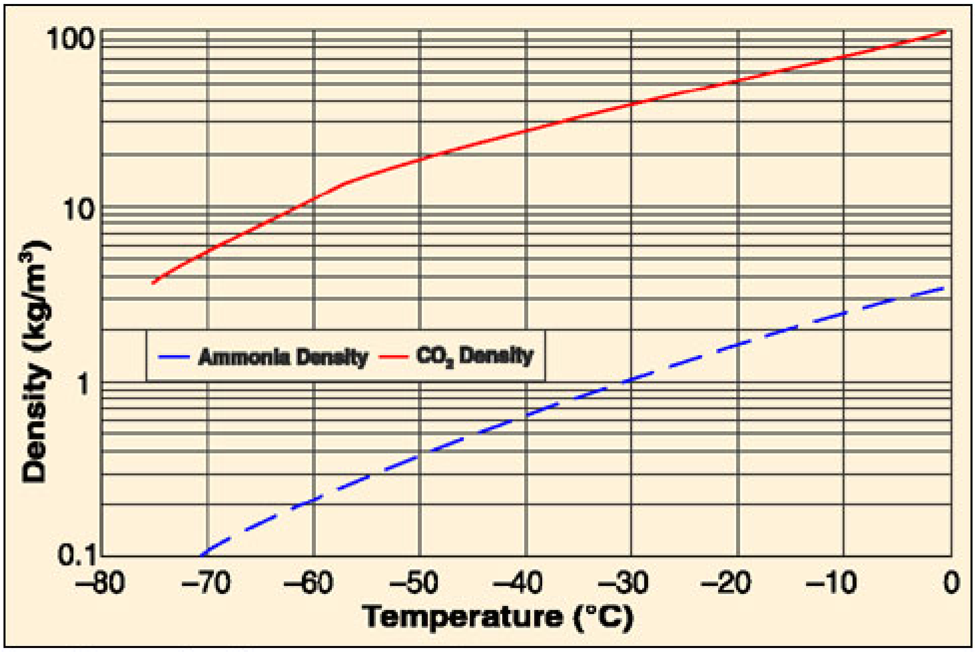

Figure 1 : Gas densities of ammonia and carbon dioxide

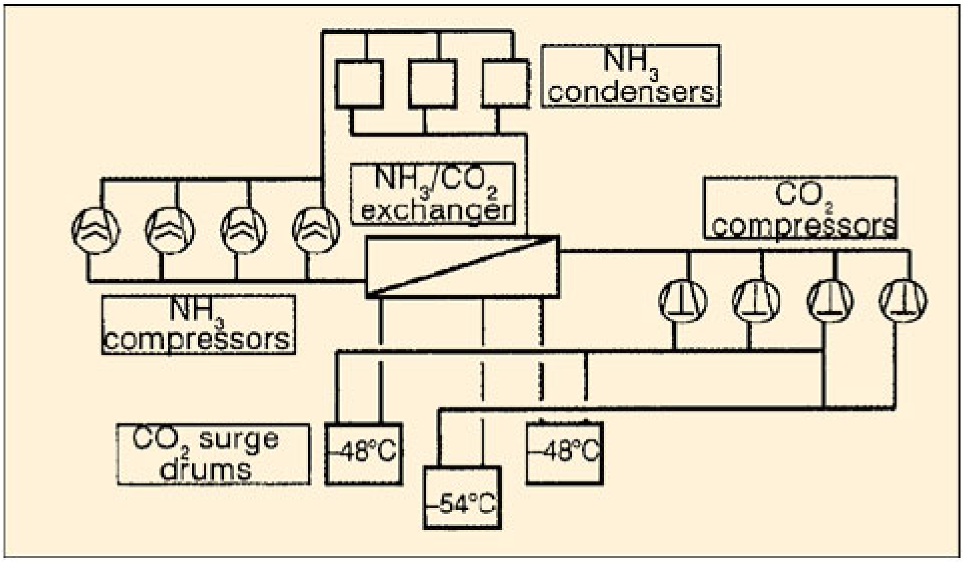

Figure 2 : Schematic diagram of the UK system

Figure 1 shows the temperature/density plot for ammonia and carbon dioxide. It can be seen that for typical condition of –40°C(–40°F) carbon dioxide gas about 40 times more dense than ammonia. Although the latent heat is about one fifth of ammonia, 300 kJ/kg (129 Btu/lb) compared with 1,400 kJ/kg (600 Btu/lb), the swept volume required of carbon dioxide is about one-eighth that of ammonia. One CO2 compressor gives the same refrigerating effect as eight similar machines on ammonia!

For the UK project, a system was adopted that has a common ammonia high side and separate carbon dioxide circuits. The plant serves two banks of process heat exchangers and a set of eight cold store air coolers. The majority of the heat load, from the process evaporators, can be extracted at a slightly higher temperature than the optimum for the cold store, which should be kept as cold as possible.

Four carbon dioxide compressors were provided, with two suction headers. One header feeds two compressors at about – 45°C(–49°F), and the other, connected to the cold room, feeds one compressor at about –55°C (–67°F). The fourth compressor is arranged as a swing standby connected to both systems with isolating valves. A single heat exchanger (carbon dioxide condenser) feeds liquid to a high-pressure receiver where it is distributed to three surge drums using low-pressure floats. On the ammonia side four screw compressors are connected to evaporative condensers with a common high-pressure receiver and an open flash economizer. Although high-pressure float control of the system was considered, a low-pressure float system was adopted to enable the installation of additional ammonia side loads at a later date if required.

It was originally intended to design the ammonia system for an allowable pressure of 18 Bar(G) (265psig) and the carbon dioxide system for 30 Bar (G) (441 psig). However a brief hazard and operability study identified that a leak of carbon dioxide into the ammonia system might cause blockage of relief valves if ammonium carbonate was formed.

To avoid overpressure of the ammonia system under these circumstances, it was decided to design both systems for an allowable pressure of 28 Bar (G) (412 psig). Therefore, it is not possible to over pressurize the ammonia system from the carbon dioxide side, even if the ammonia relief valves are blocked. In addition, pressure switches and vent solenoid valves are fitted to the carbon dioxide system to blow some gas to atmosphere if the pressure rises to 25 Bar (G) (368 psig).

Compressors, condensers and control valves for the ammonia system are readily available with a design pressure of 28 Bar (G) (412 psig) so it was possible to use relatively standard equipment for the ammonia circuit. The carbon dioxide compressors are restricted to 24 Bar (G) (353 psig) standstill and 8 Bar (G) (118 psig) running on the suction side, so additional pressure limiting systems were required to prevent damage to these compressors.

No major problems of compatibility between carbon dioxide and traditional lubricants exist, but mineral oil and its derivatives are not miscible with carbon dioxide. It is necessary in a low-temperature system to ensure that the evaporator does not become fouled with thick oil or its decomposition products. This can be avoided by selecting a non-miscible synthetic oil with low pour point, such as a polyalfaolefine. However, if nonmiscible lubricant is used then the oil return from the surge drum to the compressor must either feed liquid back to the compressor or else use an oil collecting pot, as is common in ammonia plants. The oil collecting system can be automated, but systems for non-miscible oils tend to be relatively expensive compared with the simple rectifiers which can be used with a miscible oil. A new range of polyol ester oils, miscible with carbon dioxide, have recently been developed. These ensure good oil flow in the evaporator, as in a halocarbon plant.

For the demonstration unit with the small screw compressor, a polyol ester (POE) lubricant was selected. The first selection was Triton SE170, a relatively thick lubricant with a pour point of about –25°C (–13°F). Miscibility at low temperature ensured that the evaporator would not be fouled, and the thick oil was preferred to protect the compressor bearings, as they are required to operate at high pressures. During performance testing, it was confirmed that the evaporator was not suffering from oil fouling, but the oil rectifier was not performing correctly. This problem was solved by changing to the slightly thinner Triton SEZ80 oil and making a small modification to the rectifier pipework. With these modifications in place, the demonstration unit now runs fully automatically under the control of an air temperature thermostat.

The demonstration unit: the compressor drive motor (55 kW) is in the foreground

Although the operational experience of the demonstration unit was good, there was concern about the long-term effects of oil in the process evaporators. The effect of moisture on the POE was also unknown. It was decided to use oil-free compressors for the main project to minimize the risk of future problems. Four piston compressors were selected. Each machine has three double-acting cylinders giving six equal steps of capacity control. The oil-free compressors are more expensive than the equivalent size of screw compressor but there were some minor cost savings in the cost of oil, the oil recovery system and the oil maintenance allowance that partially offset the extra expense.

Unlike ammonia, carbon dioxide has no distinctive smell, although individuals exposed to it report a strong adverse reaction. The acceptable exposure level (AEL) for carbon dioxide is 5,000 ppm, five times higher than for most other "non-toxic" refrigerants, and it is present in the atmosphere at a level of 0.03% (300 ppm). Although carbon dioxide is essentially non-toxic, it must be treated with caution, and exposure to excessive amounts of carbon dioxide can cause asphyxiation, even when there is ample oxygen in the atmosphere. At about 9% carbon dioxide in air, the body's natural respiration reflex is disrupted, and breathing becomes impossible. It is recommended that CO_2 sensors should be installed in production areas when carbon dioxide is used, particularly when those working in the vicinity are not trained technicians. Regular leak testing is also recommended. These precautions would be prudent for any refrigerant that is not "self-alarming," for example R-22 or R-404A, when used in a production area.

The demonstration unit has run for about 24 months and has proven to be extremely reliable. The main system compressors and liquid pumps have been successfully commissioned with no reported problems, and the heat loads are now being introduced as part of a phased changeover from R-22.

Carbon dioxide was selected for the low-temperature side of the plant because the only "natural" alternative was ammonia. By keeping the ammonia within the plant room and the condenser area, the charge is reduced significantly. It is estimated that the total charge that would have been required was about 20 tonnes (44,000 lbs) of ammonia, but with the cascade system this will be less than five tonnes (11,000 Ibs). In addition, at normal operating conditions none of the ammonia system is below atmospheric pressure and the risk of drawing air and water into the system is greatly reduced. If ammonia had been used to feed the cold room air coolers at –55°C (–67°F), the pressure would have been 0.7 Bar (10 psi) below atmospheric pressure, and performance would have suffered significantly at the slightest leak. The ammonia section of the cascade system is self-contained and relatively easy to maintain.

The carbon dioxide system uses much smaller pipes than would have been required for ammonia or R-22. In addition to the relative ease of installation in an existing factory, this offers many benefits in operation. The quantity and cost of low temperature insulation is reduced, so it is cheaper to install and easier to maintain. The carbon dioxide system includes a controlled vent system to maintain system pressures in the event of an emergency. To a traditional refrigeration engineer, this seems a strange thing, particularly as carbon dioxide is regularly mentioned in connection with global warming.

It must be remembered that the main effect of carbon dioxide on global warming is the result of emissions from power stations. The quantity contained in a large system is trivial in comparison to the amounts produced by burning fossil fuels to power the plant, and therefore the impact on the environment of venting small amounts to atmosphere is negligible. Carbon dioxide is also much cheaper than ammonia. At current UK prices, ammonia costs about £1.00 ($1.46 U.S.) per kilogram, whereas carbon dioxide is about one-tenth of that. R-22 and R- 404A on the other hand are about 10 times more expensive than ammonia.

The pressure in the low side of the carbon dioxide system is about 6 Bar (G) (88 psig) in normal operation. Any leak of liquid at these conditions will form a powder of "dry ice" as the liquid is dropped to atmospheric pressure, making the leak easy to locate. If the leak is from the gas space, there will be no risk of air or moisture being drawn into the system, and there is no need to fit a non-condensable gas purger to the carbon dioxide system. It is, of course, necessary to evacuate and dehydrate sections of the plant after maintenance to avoid a buildup of air and water when the system is recommissioned.

During testing of the demonstration unit, the surge drum pressure was dropped below the triple point to see what effect this would have on the operation of the plant. The pump suction strainer very quickly choked with solid carbon dioxide slush, and the pump tripped. Once the pressure rose and the solids returned to liquid the plant was restarted with no adverse effect. The time taken for the solids to clear was about five minutes.

The recent work in the UK factory has demonstrated the viability of carbon dioxide cascade systems for lowtemperature applications, and has provided the client and the contractor with valuable experience of the various advantages and disadvantage of working with this wholly familiar and yet unusual fluid. It is to be expected that continued pressure from governments, environmental lobbyists and the general public will result in increased emphasis on energy efficient systems, particularly those that use the so-called "natural" refrigerants. In this environment increased use of ammonia/carbon dioxide cascade systems for lowtemperature freezing and storage seems highly probable.

Some further development work needs to be done in the design and implementation of components and ancillary systems, particularly those associated with defrosting, but in all other aspects the technology is already proven, and is available for implementation now.

Notes

1.This system was the subject of a paper presented at the IIAR Annual Conference in Nashville, Tenn., March 2000 by Andy Pearson.