OPTIMISING INDUSTRIAL $\text{CO}_2$ SYSTEMS

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ABSTRACT

There is now a wide range of equipment choices facing the designer of industrial CO2 refrigeration systems. Secondary loop, cascade and transcritical plants all have their place and can offer unusual benefits to the designer and the operator of the plant. Most research work, particularly on transcritical systems is looking at small systems for domestic and commercial applications. Some of these findings can be scaled up to industrial plant, but in other cases better designs become more appropriate. In a few cases the small scale solution simply does not apply to large scale plant. This paper addresses the particular challenges of designing industrial systems and offers insight into ways of using existing equipment. It also suggests some ideas for future development to capitalise on the advantages offered by carbon dioxide.

1. INTRODUCTION

Carbon dioxide has been successfully reintroduced as a refrigerant in the industrial sector of the refrigeration industry. Most of these recent industrial systems use techniques that are over one hundred years old. However advances in technology in recent years offer industrial designers the possibility of using carbon dioxide in new ways with significant advantages over current technology. These advantages have not to date been investigated by researchers and there is a lack of publications about the industrial sector. The selection of the most appropriate system depends upon numerous factors, including heat extraction temperature, system capacity, heat rejection technology, and heat recovery strategy. Other considerations, such as site refrigerant policy, operator experience and availability of maintenance support will also affect the decision. Despite the range of systems covered in this analysis, some general conclusions can be drawn.

Significant research activity in carbon dioxide refrigeration and heat pump systems in response to the restrictions placed on the use of halogenated alkanes has produced a wealth of literature covering physical properties, thermodynamic performance, system arrangements and component design. These papers have been published in international journals and the proceedings of seminars, conferences and congresses, including a series of biennial conferences introduced in 1994 and arranged by the International Institute of Refrigeration with the theme of Natural Working Fluids in Refrigeration and Heat Pump Systems. However a study conducted by the author in 2003 (Pearson, 2003) showed an almost total lack of published work on industrial refrigeration systems. This study, updated in 2005 (Pearson, 2005), is shown in Figure 1.

The percentage of papers on carbon dioxide systems has grown from 7% of the total at the first meeting in Hannover in 1994 to 48% at the Glasgow meeting ten years later. The number of presentations at the IIR congresses in The Hague (1995), Sydney (1999) and Washington D.C. (2003) has also grown from a solitary commercial paper to more than 30 covering a range of subjects. In the five conferences from 1994 to 2002 there was an average of one industrial paper per meeting (out of about 100 papers at each conference) and in the three congresses from 1995 to 2003 there has also been an average of one industrial paper per meeting (out of about 400 papers at each congress). The increase in industrial papers when the Gustav Lorentzen
(Natural Working Fluids) conference was held in Glasgow in 2004 was the result of several presentations by the staff of Star Refrigeration, who were responsible for three of the four on industrial topics.

![CO2 Papers at IIR Conferences](image)

Figure 1 – Presentations at the International Institute of Refrigeration

2. **SYSTEM SIZE**

All the laboratory based research into carbon dioxide refrigeration systems appears to be focussed on light commercial equipment or smaller. This is predicated by the size of test rigs: the usual problems of sourcing sufficient motive power and heat load are amplified by the high specific refrigerating effect of carbon dioxide which means that even relatively small test rigs require a lot of power and heat, and reject a lot of heat. However the valuable lessons learned from these investigations cannot always be scaled up to industrial sized installations. In particular some of the control philosophies used in laboratory test rigs are inappropriate for industrial plant. Installations with multiple evaporators require additional consideration, as does the application of variable capacity control. Oil return from the evaporator in cascade and transcritical systems can be much more challenging, but large size also brings some benefits. It is usually possible to achieve far higher levels of oil separator performance through the use of coalescers, oil washers and active carbon filters, and if care is taken in the design then oil carryover to the low pressure side can be almost eliminated. As well as making the plant easier to operate and maintain this undoubtedly has a beneficial effect on evaporator performance. Protection of compressors against liquid carryover is essential on larger systems so direct expansion and overfed suction accumulator systems are not recommended. If a transcritical system is being used then particular care is required to ensure that sub-critical liquid cannot be trapped in any vessels or pipework, as the resultant pressures could be excessive. The size of system in question also has a strong influence on the type of compressors considered. At the high pressures required for transcritical operation only screw compressors are currently available in the larger sizes. Ongoing development might add centrifugal options to the mix, but only if small diameter high speed machines with reasonable performance can be produced. For smaller plant, and particularly high back pressure applications a wide range of reciprocating...
compressors is now available. It is unlikely however that this range will extend much above
1000m$^3$/h. For very small systems direct carbon dioxide is preferred to single pressure
secondary systems because compressors, whether cascade or transcritical, are easier to source
and because the small system does not justify the complexity of a secondary circuit. There
appears to be no upper limit to the range of secondary systems. Cascade systems can also
handle very large loads in the Megawatt range easily. However the limit for transcritical
systems currently appears to be at about 3-4MW capacity, with the vast majority of systems far
smaller than this.

3. OPERATING TEMPERATURE LEVEL

Industrial carbon dioxide systems fall rather neatly into five categories: freezer systems, cold
storage systems, chill storage systems, air conditioning systems and heat pump systems. In
some types of freezer a substantial advantage can be gained by running the carbon dioxide
system at lower temperatures than would be considered for ammonia plant. The freezing time
for plate freezers can be significantly reduced without suffering the penalties incurred in
ammonia plant when the suction gas specific volume increases to uneconomic levels. In these
freezers a second benefit is the high heat transfer coefficient achieved by the evaporating carbon
dioxide. This does not apply to blast freezers and spiral freezers, where although the lower
temperatures can be achieved, the heat extraction is dominated by the air in the freezer and so
the high heat transfer coefficients which were seen in the plate freezer example do not provide
much benefit. There are still many other advantages in all types of air blast freezers, not least
the opportunity to run a natural refrigerant with no risk of product contamination.

![Figure 2 – Current and future ranges for industrial equipment](image)

Low temperature cold storage, if it is a stand alone system, is probably most economically
served by a volatile secondary system, but if it is linked with a chill storage system then a
carbon dioxide cascade, with direct feed from the high pressure receiver to the chill coolers will
be much more cost-effective. Large chill systems are most likely to be configured as volatile
secondary systems, where the saving in glycol pumping power is the most significant
advantage. Smaller chills could be constructed as transcritical systems with current technology
if the cost and complexity of a secondary system or a cascade is inappropriate. The evaporating
pressures required for air-conditioning applications are typically in the range 10°C to 15°C.
This is too high to serve as the low stage of a cascade, so the choice here is between a high
pressure volatile secondary system or a transcritical arrangement. At present a few secondary
systems have been installed (Hutchins, 2005), but equipment for transcritical systems is not yet
available. The economic selection at the moment is biased by equipment availability towards
the volatile secondary, but this will change, and ultimately the choice will be based on whether
or not heat recovery is of interest. It is expected that carbon dioxide systems will be applied to
smaller cold and chill store systems in future, as shown in Figure 2. For heat pumps future
development is likely to be of larger systems, particularly for district heating (Pearson, 2006).

4. HEAT RECOVERY POLICY

The adoption of carbon dioxide as the primary refrigerant offers some new and intriguing
possibilities which could make heat recovery from building services installations attractive
where previously it was not. The greatest advantage of a carbon dioxide based heat recovery
system is that the compressor does not run any less efficiently than it would to chill water
without any heat recovery. This will make heat recovery an attractive supplement to
refrigeration installations where previously it would not have been considered. Another major
advantage is that the heat can be transferred over long distances within the building in the
carbon dioxide pipes, which are significantly smaller than hot water pipes would be. As the
carbon dioxide at this point is in the transcritical condition there are also none of the problems
of air or steam traps, liquid hammer and liquid leakage which might arise if the recovered hot
water had to be circulated through the building. Similarly the cold carbon dioxide (when it
comes out of the heat recovery system) is still transcritical and so it is easy to distribute. When
the refrigeration system is operating at low suction temperatures the hot water temperatures that
can be achieved are higher than those found in a typical heat reclaim system. However the
correct system configuration must be used, matched to the required temperature rise in the heat
sink, otherwise efficiency could be extremely poor.

5. OTHER CONSIDERATIONS

Several researchers have investigated various types of expansion machine including pistons and
improvement for piston expanders, but in a technology which is very unlikely to scale up to
analysis for a screw expander in a size which would be suitable for industrial systems, but
which is not yet available for transcritical pressures. Bullard (2004) reports that all types of
expander require significant added complexity and need to be considered in combination with
other auxiliary components such as a suction-liquid heat exchanger or an intercooler. The
parallel compression system described by Bell (2004) could be added to this list. All of these
auxiliaries tend to reduce the advantage of using an expander while increasing system
complexity, so it was concluded that for industrial systems there are more cost effective ways to
improve efficiency. It is noted that none of the expanders described in the literature had any
means of capacity control, and would therefore not be suited to a large industrial system.

6. LIMITATIONS

The pressure difference on low temperature systems is significant and might prompt the use of a
two stage system where single stage would have been accepted in a traditional ammonia design.
This is despite the fact that the pressure ratio of the single stage carbon dioxide system would
undoubtedly be less than the pressure ratio of the single stage ammonia system. An ancillary
benefit of this enforced constraint is that the cost of two small carbon dioxide compressors will
probably still be less than the cost of the large ammonia machine required, and the efficiency
will be substantially better. This is particularly important in process freezing equipment which has a high utilisation.

High discharge pressure is a limitation at present but product development continues to provide equipment capable of ever higher pressures. It is particularly important when designing a project on a long development cycle to be aware of the pace of change, so that maximum advantage can be taken from new equipment. Low temperature is also subject to the limit imposed by the triple point, however systems have been designed which run below 5.2 bar abs by blending carbon dioxide with other fluids, such as ethane and dimethyl ether. These would be restricted to very specialised applications. A system using d-limonene as the “carrier” fluid circulating particles of solid carbon dioxide at temperatures down to the atmospheric melting point of −78°C has also been used. In this case it is possible to recover the carbon dioxide gas at 1 bar abs and compress it so that it can be condensed at more moderate temperatures. As the pressures involved in this case are not severe – the discharge pressure would probably be about 20 bar abs – the compressor does not have to be particularly unusual, provided the system is designed to protect the compressor from very low temperatures. This can easily be done with a suction-liquid heat exchanger to raise the suction gas temperature to about −50°C.

7. FUTURE PROOFING

Given the rapid rate of change in the refrigeration industry generally and in the development of carbon dioxide systems in particular it is worth considering what can be done to accommodate future developments as they arise. Cascade systems, by their very nature, lend themselves to modular plant. It is therefore possible to plan a factory development so that it can absorb new technologies as they arise. One example is the expansion of a freezer line. It would be possible to replace the low temperature side of a two stage ammonia plant with a carbon dioxide loop, perhaps even re-using the old ammonia boosters as additional machines on the high side. This could give increased capacity and lower operating temperatures for a fraction of the price of a complete new system. In time as new machines come on the market and the high side ammonia compressors need replacement, an integrated carbon dioxide high stage with full high temperature heat recovery could be installed, operating in parallel with the ammonia plant, which would continue to provide a portion of the interstage cooling. In this way the cost of replacing the whole system could be phased over a period of ten years or more, with each stage of development providing a payback through increased product capacity, increased throughput, improved efficiency and ultimately “free” heat recovery. This approach is also the least likely to be adversely affected by increased regulation: it avoids the use of F-gases, but at the same time reduces the charge, and ultimately eliminates the use of hazardous refrigerant. It is highly improbable that legislation restricting the use of carbon dioxide as a refrigerant will be introduced: the same cannot be said for any other chemical in use for the majority of industrial refrigeration systems.

8. CONCLUSIONS

At present carbon dioxide offers a wide range of benefits, but within fairly tight constraints on operating temperatures and pressures. At higher temperatures cascade systems are also more expensive and less efficient than the best of alternative systems, such as two-stage ammonia plant. However as higher pressure compressors and ancillary components become available this situation will undoubtedly change. Compressors suitable to be the high pressure side of a two stage transcritical system will probably be available on the open market in sufficiently large sizes to suit industrial applications within the next five years. There are numerous new ways to gain maximum advantage from this technology, many as yet undiscovered. This provides a
number of opportunities for further study in component design and application. It is to be hoped that these opportunities will be pursued in industrial systems, not just in laboratory-scaled experiments.

REFERENCES


