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RESEARCH AND DEVELOPMENT FOR THE USE OF NATURAL REFRIGERANTS

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ABSTRACT

This paper presents the state of the art, overview of the recent research and development with a list of issues for main natural refrigerants. It also provides author's view to the most important issues and prospective. The paper also discusses ways to improve performance and addresses issues arising from transitioning systems with natural refrigerants from alternative to mainstream option. The focus is on CO_2 and ammonia to the greatest extent, while hydrocarbons, is mentioned briefly.

1. INTRODUCTION

We are witnesses of recent significant activities and achievements in the development of systems based on natural refrigerants. Here is the list of some:

1. Carbon dioxide:
    a. Heat pumps and water heaters
    b. Mobile air conditioning
    c. Small and supermarket commercial systems: transcritical, cascade, secondary loops
    d. Industrial refrigeration: transcritical and cascade
    e. Secondary coolant applications
    f. Expanders and ejectors
    g. Other CO_2 systems
2. Ammonia:
    a. Industrial and commercial NH_3/CO_2 cascades
    b. Absorption systems
    c. Low charge - low leak systems
    d. Indirect systems (typically ammonia)
        i. Single phase
        ii. Ice slurry
        iii. Carbon dioxide
3. Hydrocarbons:
    a. Low charge - low leak
    b. Cascades
    c. Secondary systems
4. Air
5. Water

2. FLUIDS

2.1. Status of carbon dioxide

Heat pump applications:

Currently the most attractive applications are water heaters, heat pumps, automotive air conditioning systems, and small commercial applications (bottle and beverage coolers, restaurant equipment etc…) to mention just a few. Some others are quietly pushing their way in. Even though the automotive air conditioning applications probably are of the greatest importance due to the potential numbers of units, water heaters are currently leading the way in sales at the moment with a forecast by the Japanese Government that the cumulative number of installed units will reach 5.2 million in 2010. (A remarkable increase in sales of CO_2 water heaters over the past five years is shown in the figure below with forecast for 2006).

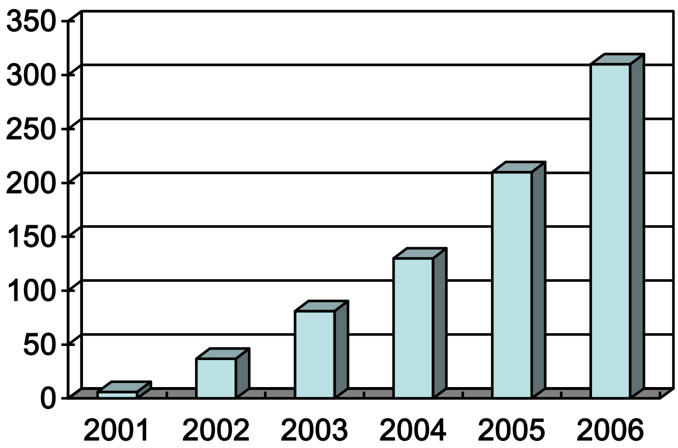

Figure 1. CO_2 heat pump water heater market in Japan (data from JARN, Special Edition Feb. 25, 2006)

Strongly supported by government and electrical utilities several manufacturers have designed different but overall similar designs (see Fig.2) of the system and various compressor types (nevertheless all rotary and hermetic). Strong market penetration pushes continuously development of new, improved components. Even COPs could be still significantly increased (currently close to 4). It is worth mentioning that the fist commercialization of the ejector was in this application (Denso) and even stronger research and development work was noted in automotive applications.

Figure 2. Some CO_2 heat pump water heaters (K. Hashimoto, IEA v.24.3.2006)

Commercialization started also in Europe but had less successful initial outcomes. Commercial (larger) sizes are developed in USA (Figure 3) but market penetration is still limited. At this point Chinese market seems to be even more promising.

Figure 3. Industrial 60kW CO_2 heat pump water heater (T. Seinel, IEA v.24.3.2006)

Mobile air conditioning applications:

The future looks bright for water heaters but the topic that is holding the industry's attention is the future of mobile air conditioning applications.

One of the major decisions that may affect the future of CO_2 as a mainstream application seems to be made: VDA (German Association of Automobile Industry) has announced their selection of transcritical CO_2 option as a solution for meeting the EU requirement that the refrigerant have GWP less than 150. At this point it is to be implemented in Europe only. What remains to be seen is their option for the same models of cars sold outside EU and what will be the choice of other OEMs for sales in Europe. This is an extremely bold decision. Introduction of that level of technological change requires not only good and acceptably priced components and systems, but high reliability of both components and systems. In addition to changes in car design, assembly lines must be modified, personnel educated, but even more service technicians should be trained along with assembly people. Service stations must be equipped with appropriate procedures and tools. In a word, numerous changes must be made and most likely some initial problems are likely to happen.

It is reasonable to expect that applications of transcritical CO_2 systems in automotive air conditioning will have the most profound impact on the future of carbon dioxide as refrigerant for various reasons. The most important is that with mass production, much greater than in any other application, reliability of the systems, compactness of the components, and simplicity of designs will be dramatically improved. Even more important: the costs should go down. In addition, the increasingly important desire of major OEMs for unification of the systems globally should expose that technology to numerous decision makers in engineering and regulatory sectors of industry and professional societies. Similarities to the scenario seen when MAC industry led R12 replacement by R134a are striking to many. That resemblance alone can generate an additional psychological effect in favor of R744 (carbon dioxide).

Nevertheless, all said above could be confronted with several historical (and current) situations in refrigerant arena. For instance, Isobutane (R290) had demonstrated excellent performance, low costs and absence of flammability incidents in residential refrigerator-freezer applications but we still do not see significant penetration of that refrigerant in some other important markets. Could that slow development happen to carbon dioxide? The truth is that automotive industry is much more globalized and pressure for system unification will be significantly stronger.

In addition, many good new fluid candidates with an extremely low GWP (first announced by DuPont, then by Honeywell, INEOS, and afterwards by several other manufacturers) may show viability and be preferential choice to many manufacturers for various reasons.

We remember ten or fifteen years ago most engineering circles were echoing skeptical comments about CO_2 related to its poor thermodynamic cycle efficiency when used in contemporary systems. Since then, several demonstration projects have led to broader acceptance of the fact that its superior thermophysical properties can be exploited to improve component and system efficiencies. In many cases, prototype components have enabled transcritical carbon dioxide systems to exceed the efficiency of baseline conventional ones. We can make a quick perusal of the state of the art in CO_2 components as compared to their R134a counterparts.

Most CO_2 compressors are 5 to 10 percentage points more efficient than currently used R134a compressors. Nevertheless, recent compressor development directions were different in the CO_2 and R134a arena with switched objectives compared to ten years ago. Carbon dioxide compressors have been aimed at reliability while recent R134a compressor development has emphasized isentropic efficiency. The result has been improved efficiency in R134a compressors that presents a challenge to CO_2 systems. On the one hand, this situation creates parity between CO_2 and R134a compressors, but it is also an incentive for the next step: efficiency improvement of CO_2 compressors.

When well designed, gas coolers with the same core volume, fin enhancements and air flow rate as conventional condensers achieve approach temperature differences of 1-2^oC. This fact was unexpected and it offers great opportunities for further size and cost reduction, when properly exploited

Evaporators for air cooling can not take full advantage of the good heat transfer offered by CO_2 due to the dominance of air-side resistance, but for liquid cooling there is a clear advantage. The accepted existence of an internal heat exchanger in CO_2 systems has a positive effect on reducing the consequences of imperfect refrigerant distribution but the recent appearance of results and designs for an internal heat exchanger for R134a systems may take advantage of that as well. Reduction of refrigerant side pressure drop in heat exchangers will provide more benefit for R134a systems than CO_2 systems. However, extruded tubes with reduced port sizes offer advantages on the air side and CO_2 requires smaller ports than for R134a. In other words, there is a need for new and creative approaches in CO_2 evaporator design that will take in account thermophysical properties of CO_2. In addition, new designs of air side enhancements that will allow for better condensate drainage will result in decrease of air side resistance that will consequently benefit CO_2 with its better refrigerant side heat transfer characteristics. Even though the current designs of evaporators and gas coolers for CO_2 are almost identical in size and weight to their R134a counterparts – and thus asymptotically cost the same for similar production volumes – further efforts are needed to generate designs with reduced cost.

A major problem for CO_2 systems that use the conventional reversed Rankine cycles is expansion losses. Significant design and even research activity is currently focused on these and related issues to improve operation in that area. One of the options is recovering expansion work using either mechanical expanders of various designs or ejectors. The results of these activities might prove to be crucial in determining new ways of improving CO_2 systems. Some issues in expanders are:

1. Choice between an expander integrated with compressor in a single unit or separate expander that boosts existing conventional compressor that controls capacity

2. If integrated, find a way to effectively control the optimal operating parameters of the system
3. Efficient and simple design for the expander in expander-compressor

The issues in ejector design are similar: good geometry and efficient control. The ejector seems to potentially offer lower cost and easier control but at this stage of ejector design, its efficiency is lower than that of a mechanical expander. An ejector can compensate for that shortfall and even can outperforms an expander in the same system due to positive secondary effects in the system. An ejector also provides most of the advantages of flash gas bypass: reduced pressure drop in the evaporator, better refrigerant distribution and even a slightly overfed evaporator.

Unfortunately both an expander and an ejector (and some other potential improvement options) compete for the same potential which the internal heat exchanger already uses at lower complexity and cost. For that reason any analysis that addresses either expanders or ejectors must include an internal heat exchanger as a part of the system.

Multistage expansion offers other additional opportunities for cycle efficiency improvements, but that option requires either multistage compressors or designs that allow economizer ports.

In order to achieve further cost reduction when compared to conventional R134a systems, special attention should be focused on the simplifications of the system: better location of the components, reduced oversizing of components and safety, better flexible piping etc. Research on control options are expanding beyond ideal high side pressure control to investigate simple orifice tubes with improved characteristics, which offer significantly lower cost.

To give a credit to CO_2 system designers, they are working within the physical space currently occupied by R134a components for various reasons. One of the significant limitations for CO_2 systems in mobile air conditioning applications is the need to replicate current systems in every way. If or when CO_2 is accepted as the standard, the systems will be able to be different from the systems we know today in many respects, allowing further optimization of CO_2 systems in the future.

It appears that performance of CO_2 in heat pumping applications is universally unchallenged, regardless of the application. Nevertheless, these advantages seem not to be sufficient to break the ground for mass production neither in mobile air conditioning systems as add on benefit nor for residential applications at this moment. Regardless of that situation, the author is fully convinced that the heat pump advantage will become more important both for mobile applications (when either more efficient engines or electric motors will be used) and for residential applications.

At high outdoor ambient temperatures, energy efficiency remains a weak point in the argument for CO_2. In mobile air conditioning systems an ambient temperature of 35°C is currently seen as the break even point for COP, beyond which it is difficult for CO_2 to compete with R134a. Seasonal efficiency calculations that integrate efficiency over wide range of operating parameters helps to promote CO_2 because of its superior efficiency at lower heat rejection temperatures. With the same system external volume and air flow rates, CO_2 systems offer more refrigeration capacity. The same holds for the compressor –typical displacement is 5 to 7 times smaller. Nevertheless the overall size and weight is greater for CO_2 compressors in most cases. Some recent prototype CO_2 compressors have been made smaller and lighter than their R134a counterparts; this trend should be sustained in order to increase attractiveness of the systems.

To ensure a stronger presence in the market for refrigerating and air conditioning systems, it will be helpful to try to improve the efficiency of CO_2 systems at higher ambient conditions (even the author does not see that as the major issue because of small number of operating hours in most climates), while improving control strategies that do not significantly penalize efficiency when reducing capacity at lower ambient conditions. In other words, control strategies that exchange the excess capacity of CO_2 systems at lower ambient temperatures for efficiency benefits could have great impact on CO_2 system development.

Commercial applications:

The major boost to realize and improve small transcritical systems for commercial applications came after the Coca Cola Company's announcement at the meeting in Brussels together with Unilever and McDonalds that they have chosen transcritical CO_2 system as the environmentally friendly replacement for R134a systems instead of R290 or Stirling cycle. This decision had triggered significant push in small hermetic compressor design so almost all major manufacturers have their products ready: Danfoss, Embraco, Sanyo, …. Sanyo announced recently installation of 5000 new bottle cooler units to be placed at Beijing Olympics (Fig. 4) in addition to other manufacturers.

Figure 4. SANYO CO_2 horizontal two stage rotary compressor and cassette type bottle cooler unit

All CO_2 systems developed in that process have outperformed their R134a counterparts in both capacity and efficiency. The author does not see any technical issue that is holding the realization of the concept and application.

Transcritical systems for supermarkets started to gain momentum on the market, after first secondary loops using CO_2 as a volatile coolant and later cascade systems have paved the road for CO_2. The most important element is existence of fine operating compressors of appropriate size and good engineering practice. The data available from the first few years of operation are very favorable to CO_2.

Cascade systems continue to attract attention in both supermarkets and industrial applications. The balance between their slightly higher efficiency compared to transcritical approach vs. simpler and probably less costly CO_2-only systems will determine the winner.

Secondary loops with CO_2 as a coolant are very good solution and are still going strong for both commercial and industrial, mostly for low temperature applications. Significant new data on heat transfer are becoming available but most important is the progress in CO_2 liquid pumps and pumping and cascade heat exchangers.

Industrial refrigeration applications:

Introduction of CO_2 in industrial refrigeration is happening at vastly different ambient compared to automotive and commercial. Engineers used to dealing with ammonia see CO_2 as a reasonable approach, the equipment is similar, and they are used to working with different systems, mostly custom designed. In other words, unlike the significant confrontation facing CO_2 in other circles, there is a cooperative atmosphere between NH_3 and CO_2 among industrial refrigeration professionals. One of the significant differences is also the fact that the lower first cost of CO_2 systems is more clear in that segment than in mobile and commercial application. Another difference is that the main customer supports the change for operational, safety and also public relation reasons (among them is the environmental element).

Cascade systems are definitely the most dominant solution at this point. Secondary loops are not so commonly used as in the commercial sector. It is important to notice a definite trend towards CO_2 only systems (which are transcritical for a small period of annual operation) even though not so many new installations are reported at this time.

2.2. Status of ammonia

Ammonia is probably the only naturally occurring fluid that maintained acceptance as a refrigerant almost exclusively in the industrial refrigeration segment because of its excellent properties, ease of achieving high efficiencies, and low cost. That application is pretty safe for ammonia but there is a potential for expansion into other areas. Everyone is likely to agree that the only option for using ammonia in any other refrigeration application requires the existence of some other fluid, in either secondary loop options or with cascade design that will minimize risk to the general public. Good applications for ammonia are those that already use chillers, like supermarkets or air conditioning of commercial buildings. For each these applications it is crucial to have a system with:

a) extremely low charge
b) very low leak rate

To achieve very low charge either plate or microchannel heat exchangers are required. The current lowest charge at small capacity level (around 50kW) for both water and air cooled systems are approximately 20 g/kW refrigeration capacity. Issues with a water cooled condenser are the need for another secondary loop that reduces efficiency and increases cost, while air cooled systems (with microchannels) means higher discharge temperatures.

Many engineers identified the need for a semihermetic compressor to reduce leak problems. That idea is associated with material compatibility issues. Typically copper windings and insulating materials are incompatable with ammonia, specifically at higher temperatures and with water content. Aluminum windings have been tried but without good success so far. Currently available semihermetic compressors for ammonia use a canned rotor approach that reduces the efficiency of the motor. None of current designs are very successful and further breakthroughs are needed to realize good semihermetic ammonia compressor.

Serious discussions were generated to filer better oil approach: miscible (PAG) and immiscible (PAO, AB, mineral,…). Unfortunately there is still no consensus in professional circles.

2.3. Status of hydrocarbons

Propane and isobutane are probably the most frequently used HCs for refrigeration (excluding the chemical industry). Propylene was also tried with success in some cases but did not generate significant follow-up projects. Isobutane is very well accepted in small, household refrigerators. These systems have only a small amount of refrigerant and are factory sealed thus reducing potential flammability concerns. To author's best knowledge, there is no any alarming safety record for hydrocarbon system in household refrigerators. Hydrocarbons are excellent refrigerants (thermodynamic and thermophysical properties are good) and their material compatibilities are superb which with low cost for them and their lubricants provides a basis for inexpensive but unfortunately flammable systems. This solution is definitely appropriate wherever compatible with safety requirements.

Charge minimization is essential for reasonable acceptance. Current lowest specific charge for 1-1.5 kW systems is 8g/kW in evaporator, 22 g/kW in condenser, while compressors typically store (good part in oil) more than 30 g at small capacities about 1-1.5 kW.

3. CONTRIBUTION OF NATURAL REFRIGERANTS TO THE FIELD OF REFRIGERATION AND CONDENSATION

Natural refrigerants are very often referred as “alternative”, implying those that probably will never become the mainstream option. Whether this assessment will stay a reality is a function of various factors and circumstances. Nevertheless, regardless of the outcome natural refrigerants, and CO_2 in particular, have already made a great impact on the development of refrigeration area.

Typically, every new application for carbon dioxide has introduced a new design feature for improving efficiency, compactness or aesthetics. Very often these improvements have gained acceptance and were applied to other refrigerants and systems as well. An excellent example is the application of microchannel heat exchangers as evaporators (MCHEs for condensers was already being done). That is one of the reasons why successful CO_2 systems and components designs are rightfully challenged on the basis of cost parity. Some CO_2 refrigeration designs were several times smaller for the same capacity and still more efficient than conventional systems, because they represented significant technological advances.

Competition between R134a systems vs. transcritical CO_2 systems in automotive sector generated great improvements in efficiencies for both systems. Originally, R134a systems were not designed for efficiency but had been optimized for lightweight components and systems, quick pull-down and more than anything else cost. In an evolutionary way over last ten years we have witnessed – and to great extent participated in – various improvements in system efficiency and overall performance. These exceptional improvements in efficiency result in an demonstrated potential (of which a good portion is realized) of greater savings in only one year than the entire research expenditures for all CO_2 systems.

4. FROM ALTERNATIVE TO MAINSTREAM SOLUTION

With the exception of ammonia in industrial refrigeration, none of the natural fluid options have risen to the level of mainstream application so far. It appears that CO_2 might be on the way to become the first fluid to reach that level, at least in some applications. The heat pump water heater is a mature application that has found its acceptance, at least in Japan where market rose to almost a million units per year (see Fig. 1). Other heat pump options, even excellent applications where CO_2 has a comparative advantage, are far from this level of realization.

Expected commercialization in the light commercial market (bottle coolers) has not materialized so far even though the units are technically well developed and a reasonable competition among manufacturers is present.

Acceptance of any CO_2 solution for mobile air conditioning applications is extremely important for development because of: a) required technical level of components and the system and b) the market potential. Potential numbers of units for mass production would dramatically change manufacturing costs and improve quality, thus opening new possibilities.

None of the systems or solutions will be implemented on the significant scale without rational analysis and compelling reasons. That includes but is not limited on the cost, reliability, weight and size of the components and systems. Reasons for change usually fall into one of two categories: mandated change or compelling economic benefits (for either first or recurring cost). The greatest push for natural working fluids is coming from academia where knowledge and appreciation of these considerations is almost non existent. Academia is more interested in efficiency, and to a lesser extent to compactness or weight. These metrics are easy to quantify. The race for more elegant, more compact, more reliable and lower cost is attractive for enthusiasts, and success in these realms is not as easy to demonstrate or quantify. To make components and systems more reliable and extremely low cost that are able to compete on the market with existing systems requires significant effort, knowledge and investment, but it is the next step. Crucial to this step are the engineers at companies interested in acquiring new markets and developing creative new technologies. Ideas and sometimes solutions should move from interesting academic laboratory exploration into the laboratories of those that will be able to make a business case for them.

Natural working fluids are going though the same process as any new idea: mild support of those that might benefit from that approach in the future and fierce opposition of those that may lose if it is realized.

Even if the first prototypes and maybe even some production numbers are realized on the market, these products will not survive unless they have real advantages over their competitive technologies. Perhaps in some places that element is overlooked and too much help from legislation is expected (e.g. by tax breaks or by banning competing technologies), but this is a bad way to expect success. Only by realizing systems with clear economical and operational advantages will natural refrigerants be accepted. Unless the full costs of environmental risks are internalized into refrigerant prices, environmental benefits of natural refrigerants (zero ODP and GWP) should be treated as additional reason and attractiveness but not the only reason why we should expect someone to buy the product.

5. CONCLUSIONS

This analytic overview, so generic in title as to cover all natural refrigerants, was mostly focused on CO_2 and NH_3 systems being the most active recently and closer to commercialization at this point.

We are witnessing great progress in improvements of the systems with natural refrigerants lately. Public interest is steadily increasing. Some applications (heat pump water heaters in particular) are entering in mature production phase. Legislative support (mostly in Europe) is getting stronger. Nevertheless we are witnessing slow penetration of carbon dioxide technologies in some areas, while technological pipelines are full and filling even more. There is a clear need for more work on real production and marketing issues by those that see market opportunities.

The introduction of new fluid(s) with very low GWP that have good drop-in performance could slow the process, or accelerate it by presenting challenges for further improvements in efficiency, simplification of the components and systems and consequently a reduction of cost.

The logical question to ask is how to transform great enthusiasm of thousands of supporters of the natural working fluid approach, bright ideas and innovative solutions of numerous creative engineers into a real impact on the economy and mankind? Is there anything missing besides time for the idea and public awareness to spread? Could an overly extensive incubation period for natural working fluids become too long so that enthusiasm will slow down? There is always the possibility of becoming the "perpetual alternative". Stirling machines are a good example with more than 100 year long history of mostly unsuccessful attempts.