This keynote paper was presented at the XXth International Congress of Refrigeration in Sydney, Australia, in September 1999. It focuses particularly on various applications using carbon dioxide as a refrigerant. This paper provided an introduction to a wide range of papers on carbon dioxide, an old refrigerant that is now attracting renewed interest.

Refrigeration, Air-conditioning and Heat-Pump Systems for the 21st Century

by

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I. INTRODUCTION: REFRIGERATION, AIR-CONDITIONING AND HEAT-PUMP TECHNOLOGIES AND FUTURE STRATEGIES

I.1 Technological shifts

The mechanical refrigeration industry has experienced several technological shifts throughout its history. The compression-evaporation process, invented by Evans and Perkins between 1805 and 1834, has played an important role in the development of the “heat-pumping” industry.

Discovered in 1744, ammonia exhibited outstanding properties as a working fluid. Its first successful application came in an absorption plant developed and patented in 1859 by Ferdinand Carré. The reason ammonia was used with absorption technology, and not in compression machines, was that no reliable ammonia compressors were available. In 1876, Carl von Linde built his scientifically designed ammonia compressor.

Carbon dioxide (CO₂) was first solidified in 1835 by the French physicist Thilorier and used as a cooling medium (dry ice). The English company J. & E. Hall started manufacturing two-stage plants in 1889. This can be considered as the starting point for the widespread use of CO₂ in mechanical refrigeration, and especially within marine applications.

Another technological shift was, however, already on the way, initiated by the invention of a new generation of refrigerants, which could be produced with hydrocarbons as raw materials. Later to be known as CFCs and HCFCs, these new substances were developed by the Belgian Swarts, during the period 1893 to 1907. From about 1930, they were manufactured using large-scale production processes.

This development changed the world of refrigeration. By replacing hydrogen with different halogens such as fluorine, chlorine and bromine, one could “design” and produce a refrigerant with specified properties. The new refrigerants were safer for the local environment, i.e. did not explode or produce a worrying odour during leakage. They were easier to handle and less aggressive with certain construction materials. Copper and aluminium could now be used in refrigeration plants.

The new generation of refrigerants came into use at a remarkable speed. In 1940, the marine refrigeration market was divided between CO₂ (80%) and ammonia (20%). During the following 50 years, R22 almost completely took over. In large-scale industrial applications on land, however, thanks to its efficiency and low cost, ammonia has maintained its position.

Yet another technological shift was the development of driving motors, making it possible to increase speed and reduce compressor size drastically. Speeds between 1500 and 1750 rpm became common around the Second World War. When CFCs and HCFCs came onto the scene around the 1930s and 1940s, it also became possible to develop hermetic compressors, and this paved the way for low-capacity household refrigerators. It is fair to say that this opened the enormous domestic market that made refrigeration available in homes and raised the quality of life of people all around the world. These changes were made possible by innovations creating enormous markets for new products, and thus industrial opportunities.

Today, we are again in the midst of a historical technological shift and this time the need to preserve our global environment is the main driving force. Two global concerns are affecting our industry: ozone depletion and global warming. The Montreal Protocol (1987) was the first international agreement to set up a schedule
for reduction and phase-out of the production and consumption of ozone-depleting substances. CFCs, and later HCFCs, became a part of this phase-out plan. The other important international scheme is the Kyoto Protocol, which was established 10 years after the Montreal Protocol in order to reduce emissions of global warming substances and requires the active involvement of several players (Table 1).

<table>
<thead>
<tr>
<th>Players</th>
<th>Achievements</th>
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<tbody>
<tr>
<td>Universities</td>
<td>New knowledge and new candidates</td>
</tr>
<tr>
<td>Research institutes</td>
<td>New technology</td>
</tr>
<tr>
<td>Manufacturers</td>
<td>New products</td>
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<tr>
<td>Engineering companies</td>
<td>New solutions</td>
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<tr>
<td>End users</td>
<td>New demands</td>
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<td>Governments</td>
<td>New policies</td>
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The task of eliminating CFCs in the refrigeration, air-conditioning and heat-pump fields is a much bigger operation than most people outside the industry are aware of. It is estimated that the value of CFC-dependent equipment worldwide is of the order of USD 200 billion, and that units and plants may be counted in hundreds of millions.

I.2 Strategies for future development

The first years after the Montreal Protocol was established in 1987 were characterized by uncertainty in the international refrigeration, air-conditioning and heat-pump industry. Now, however, the international community seems to agree on two main strategies designed to achieve robust, sustainable, clean refrigeration, air-conditioning and heat-pump technology: “chemical” and “natural” strategies (Table 2).

<table>
<thead>
<tr>
<th>Main issues</th>
<th>“Chemical” strategy</th>
<th>“Natural” strategy</th>
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<tbody>
<tr>
<td>Prerequisite</td>
<td>Use of standard Evans-Perkins cycle from 1834 (1805) and standard pressure limits</td>
<td>Use of naturally and ecologically safe fluids as refrigerants</td>
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<tr>
<td>Development task</td>
<td>Finding new synthesized fluids to suit the standard Evans-Perkins cycle</td>
<td>Adapt thermodynamic cycle and equipment to fluid and condition of the application</td>
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<tr>
<td>Goals</td>
<td>To achieve efficiency and safety that are equal to or greater than that of present (CFC) systems</td>
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<tr>
<td>Environmental characteristics</td>
<td>Both known negative environmental effects (GWP) and possible unforeseen consequences</td>
<td>All uncertainties are eliminated. No unforeseen environmental effects</td>
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The “chemical” strategy is to develop new, complex, synthetic working fluids without ozone-depleting effects. HFCs - the new class of working fluids - are largely compatible with CFCs and HCFCs and thus can be used in just about the same equipment as before. This is an important advantage. At the moment, the most important alternative refrigerants for both new and retrofit applications are the HFCs, but they have been introduced at a far slower rate than expected. A drawback of this strategy is that it promotes substances that are not naturally occurring and may give rise to unforeseen global environmental effects. It should be borne in mind that it took roughly 50 years before we discovered the flaws of CFCs and HCFCs. Have we remembered to ask all the relevant questions this time? If not, how long will it take, and will the answer dictate another phase-out? HFCs are known to exert marked greenhouse effects and are therefore included in the basket of substances regulated by the Kyoto Protocol.

The “natural” strategy deals with using substances that are naturally present in our biosphere, and then developing processes and equipment for these fluids. Such natural fluids include atmospheric gases (air, nitrogen, carbon dioxide and rare gases), water, hydrocarbons and ammonia, all with known and controllable effects on the global environment. Hydrocarbon blends, as well as pure hydrocarbons,
are used in residential heat pumps, mainly in Europe. Technological development and improved safety measures have reduced safety hazards and improved public acceptability. The number of hydrocarbon heat pumps is still limited, but the latter are expected to play an increasingly important role during the coming years in small- and medium-capacity heat pumps. The argument against natural fluids is that some are flammable, others are toxic, their energy efficiency in traditional cycles may be lower than that of the fluids they replace, and still others require higher than classic working pressures. However, these challenges can be dealt with effectively!

It should be emphasized that society depends on both strategies in order to achieve goals inherent in international agreements. The chemical industry will need to find solutions to our short- and medium-term needs. We would never have been able to begin CFC reduction without HFCs. We also need the natural strategy, although in some cases, developing new equipment may take longer. On the other hand, this will yield robust, long-term solutions. Therefore, we believe that the role of natural working fluids will become increasingly important during the 21st century. In this paper, we will present some examples of important heat pump technologies successfully applying natural working fluids.

II. APPLICATIONS USING NATURAL WORKING FLUIDS

II.1 Residential air conditioning

Residential air-conditioning systems can be divided into room air conditioners (RACs) and packaged air conditioners (PACs). RACs are usually of the window or the ductless split type, and generally service one or two rooms. PACs are somewhat larger in capacity and will often cover the heating and/or cooling demand for an entire residence. PACs include the so-called unitary systems used with ducted air distribution (especially in the US), and also cover light commercial units used in restaurants, smaller offices, etc.

In 1997, the overall market for residential air-conditioning systems was 34 million units, of which 24 million were RACs and 10 million were PACs. The largest markets for such equipment are: USA (10 million units), Japan (7.1 million units) and China (5.5 million units). It is estimated that the world market in 2000 will be somewhere between 36 and 38 million units.1

The majority of RACs and PACs installed still operate with R22. Over the past few years, however, units using R407C and R410A have been introduced, and it is expected that these will cover most installations from now on. In Northern Europe, and especially Sweden and Germany, hydrocarbons have been used successfully, but compared with the overall market worldwide, the number of units involved is low. As an alternative to HFCs, CO₂ as a working fluid has attracted the attention of several manufacturers and research institutions.

A detailed simulation study on the performance of R22 and CO₂ in residential heat pumps gave quite promising results.2 Figure 1 shows the flow circuit.

In order to verify the theoretical results, an R22 unit and a prototype CO₂ system were set up in SINTEF’s Laboratory. The main experimental results are shown in Figures 2 and 3. In air-conditioning (AC) mode, the COP values of the CO₂ unit are slightly lower compared with the R22 unit. In heat-pump (HP) mode, the COP of the CO₂ unit is slightly higher than that of the R22 unit.3

In conclusion, the system efficiency (COP) of the CO₂ system is already competitive with that of the R22 system in both modes of operation. The CO₂ heat exchanger design concept applied is optimal neither from a gas cooler point of view, nor from an evaporator point of view. Water retention has been a problem, and this has also caused fluctuating system pressures. The CO₂ compressor has not performed optimally in some of the experiments, owing to worn bearings and leakage through the shaft seal. It should also be borne in mind that all components used in the plant have been developed for mobile air conditioning rather than RACS/PACs. It should be mentioned that it is not the absolute COP level, rather the difference in COP between CO₂ and R22 that is important. Based on the above, there should be room for further improvements in the performance of the CO₂ system.

II.2 Heat pump water heaters

CO₂ is more or less ideal for applications where heat rejection is needed at a gliding temperature, as in heat pump water heaters (HPWH). The transcritical process introduces a gliding temperature at heat rejection instead of condensation at constant temperature. The market potential for heat pump water heaters is large. Roughly 20% of the energy use in
residential and commercial buildings concerns water heating. In addition, there is a substantial need for water heating in industry, where tap water heating often may be combined with refrigeration and/or freezing, by utilizing the cold side of the system.

Nekså, Rekdal et al.\textsuperscript{8,9} describe experimental results obtained using a CO\textsubscript{2} HPWH system. These results show that CO\textsubscript{2} is very well suited as a working fluid for tap water heat pumps. Energy consumption can be reduced by 75\% compared with electrical or gas-fired units when tap water is supplied at 60\(^\circ\)C with ambient air as heat source. Figure 4 shows the flow circuit and the process in the Ts-diagram. Figure 5 shows measured heat-pump COP as function of the evaporation temperature. The tap water is heated from 8\(^\circ\)C to 60\(^\circ\)C, these being typical Norwegian conditions. Heat-pump COP is defined as the heat output divided by the electric power input to the compressor motor.

II.3 Commercial refrigeration

Commercial refrigeration is another application area with a large market potential but in which refrigerant emission is a problem. Nekså, Girotto et al.\textsuperscript{10} describe the possibility of using CO\textsubscript{2} as the only refrigerant in a system with heat recovery. The supermarket refrigeration concept is based on self-contained display cabinets with CO\textsubscript{2} refrigeration units. Figure 6 is a diagram of this type of system.

The refrigeration units placed in each cabinet reject heat to a waste heat recovery loop. By utilizing the transcritical CO\textsubscript{2} process, it is possible to achieve a large temperature glide in the loop, typically 50-60 K, and a correspondingly low volume flow rate. Waste heat with a high temperature (70-75\(^\circ\)C) is available for tap water and/or space heating. Excess heat is rejected to the ambient air by direct heat exchange and, if necessary, by using an auxiliary chiller.

System simulations for a medium-size supermarket have been carried out. Optimum brine supply and return temperatures to the cooling and freezing cabinets were identified. A comparison of the CO\textsubscript{2} system and a conventional R22 system with respect to the overall energy consumption of the supermarket for 1 year of operation in a southern European climate was carried out. The CO\textsubscript{2} system was found to reduce energy consumption by 32\% compared with the R22 system.

The CO\textsubscript{2} units can also be equipped with a condensing unit in order to reject the heat directly into the shopping area where space heating is required. During the warm season when a heat surplus arises, the waste heat recovery loop is used to remove heat. This concept reduces the power demand for the refrigeration units to the same level as for the baseline R22 system, and the resulting overall energy consumption of the supermarket will then be further reduced.

II.4 CO\textsubscript{2} automobile air-conditioning and heating systems

Between 25 and 30 million new automobile air-conditioning systems are produced every year\textsuperscript{11} and are installed as a standard feature in over 50\% of new vehicles. Refrigerant emissions per system have been reduced as a result of technical changes in the transition from R12 to R134a, but automobile air conditioning is still the dominant source of R134a emissions released into the atmosphere. Of the 84 000 metric tons of R134a produced in 1996,\textsuperscript{12} most were destined to supply this fast-growing market.

Standard automobile air-conditioning systems have an open-type compressor that is belt-driven from the engine. The evaporator is located in the HVAC unit with the heater and air-circulation fan, and the condenser is located in front of the radiator. Refrigerant emissions are relatively high as a result of extreme operating conditions, the use of an open-type compressor with shaft seal, and flexible hose connections.

Lorentzen and Pettersen\textsuperscript{13} were the first to report experimental results on a prototype CO\textsubscript{2} system for automobile air conditioning. A comparison was made between a state-of-the-art R12 system and a laboratory prototype CO\textsubscript{2} system with equal heat exchanger dimensions and rating point capacity. Although simple cycle calculations indicated that the CO\textsubscript{2} system efficiency would be inferior, a number of practical factors rendered the actual efficiencies of the two systems equal. Thus, in 1992 the conclusion was that a competitive system could be realized based on a non-toxic, non-flammable, zero-ODP and zero-GWP refrigerant.

The CO\textsubscript{2} system operates in a transcritical cycle, i.e. with supercritical high-side pressure. Owing to the low pressure ratio in this cycle, compressor efficiency is higher than for normal refrigerants. Efficient heat transfer also contributes to high system efficiency. Due to the gliding temperature in the “condenser,” the air
inlet temperature is approached to within a few degrees by the exiting refrigerant. This temperature approach exerts a significant effect on the system COP, since the throttling loss is greatly reduced by lowering the minimum heat rejection temperature.

Earlier studies on the TEWI of automobile air-conditioning systems were based on modelled COP data only. Yin, Pettersen et al.4 published TEWI data based on measured power consumption for a state-of-the-art R134a system and a prototype CO₂ system. The results show that the CO₂ system will have significantly lower TEWI than the standard system. Some typical data for US regions are shown in Figure 7, indicating 30%-50% reduction in TEWI.

In addition to the development of compact, efficient and reliable compressors, work is progressing in the area of heat exchanger design and development. Pettersen et al.5 reported results for compact and lightweight heat exchangers adapted to CO₂. Recent “parallel-flow” heat exchanger designs use extruded micro-channel tubes with 0.8 mm port diameter, and header designs optimized for size and mass reduction (Figure 8).

Modern cars with fuel injection engines often have insufficient waste heat for heating of the passenger compartment during the winter season. A prolonged heating-up period and slow defroster action are unacceptable both in terms of safety and comfort. Supplementary heating is therefore necessary, and one attractive solution may be to operate the air-conditioning system as a heat pump. CO₂ systems may have special benefits in heat-pump mode, since high capacity and COP can be achieved also at low ambient temperatures. Hafner, Pettersen et al.6 proposed an advanced circuit for reversible cooling and heating.

II.5 Heat pumps for drying heat-sensitive materials

Drying operations typically represent 10%-15% of industrial energy consumption in developed countries.7 Heat pumps have found their industrial applications in drying of materials of biological origin. The dominating application of industrial heat pumps is drying of various types of food products and wood. Heat pump dryers have several advantages compared with oil/gas-heated systems and natural drying:
- Improved product quality due to a lower drying temperature and non-reliance on ambient air conditions, including problems with insects and birds. In addition to improved quality, this will also provide better utilization of raw materials and reduced spoilage;
- Reduced energy consumption due to the COP of the heat pump (typically 4-5). In addition to the COP, the energy consumption will depend on the thermal efficiency of the dryer. Obtaining low energy consumption will therefore also depend on dryer design and operation;
- Heat pump dryers represent environmentally friendly technology due to a closed-loop drying system with no exhaust gas from the dryer, and low energy consumption.

The COP of the heat pump is given by: $COP = Q/W$, whereas the SMER (Specific Moisture Extraction Rate) number is given by $SMER = COP/dh/dx$ (kg water/kWh). The COP is the heating coefficient of performance, and dh/dx is the thermal efficiency of the dryer. In order to achieve the highest SMER number possible, industrial heat pump dryers should be designed according to the following “design rules”:
- Lengthwise, not crosswise, operation due to a higher relative humidity at the dryer outlet;
- Countercurrent, not co-current operation, due to the sorption characteristics of the material to be dried;
- Continuous, not batch, operation, due to the lowering of capacity and efficiency during a batch process;
- The highest possible inlet temperature in the dryer should be achieved thanks to improved thermal efficiency and capacity;
- The lowest refrigeration capacity possible should be used, provided that the desired production is achieved (oversizing will increase dh/dx and reduce SMER);
- The choice of evaporating and condensing temperatures of the heat pump should be the combination providing the best COP and dh/dx: an optimum might exist.

Industrial dryers used today are of an adiabatic design, meaning that the air is being cooled as it passes the product to be dried (as water evaporates). An adiabatic design will limit the production capacity of the drying plant. By having heat supplied, for instance, part of the heat pump condensing capacity, in the drying unit together with the product that is being dried, a non-adiabatic design is achieved. This might considerably increase dryer capacity. Adiabatic and non-adiabatic (isothermal) drying are shown in the humid air diagram in Figure 9.
At NTNU-SINTEF in Trondheim, Norway, a new non-adiabatic heat pump dryer with ammonia as working fluid was constructed. The flow sheet of this dryer is shown in Figure 10. The heat pump dryer was designed to have the highest possible SMER number and capacity.

The above-mentioned design criteria for heat pump dryers were followed in this plant. Results from continuous drying experiments show SMER numbers up to 4.7 kg water/kWh, and increase in the drying capacity (compared with adiabatic drying) of 380%. A non-adiabatic design will, therefore, be more compact and involve lower investment costs than an adiabatic design. With respect to the SMER number there is not a big difference between adiabatic and non-adiabatic design. This is due to approximately the same COP and also the same thermal efficiency.18

Drying, together with refrigeration, will be important preservation methods for food products in the next millennium, due to rising population and increasing consumption of ready-to-eat food. Heat pump dryers will represent an actual technology for the drying of heat-sensitive materials due to the need to take better care of raw materials and to improve the quality of the dried product. Energy efficient and environmentally friendly plant design can be achieved by following the design rules listed above and using non-adiabatic design and natural refrigerants. In the coming years, research should be performed on component, system and process design on the heat pump and drying unit. Pre-processing and handling of raw materials and dried products should also be subjected to scrutiny. Further research should also be performed on thermal, sorption and rheological characteristics of raw materials and dried products.

III. CONCLUSION

In order to phase out and reduce ozone-depleting and global-warming gases, the refrigeration, air-conditioning and heat-pump industry and society need new solutions and new technology. This need has triggered a major technological shift. In order to achieve our common goal, a lot of hard work is needed, and we have to make use of the skills and imagination of all enthusiastic research and development groups in universities, research institutes and industry. The main challenge when applying natural working fluids is to build safe and reliable systems that are able to compete with conventional HFC systems in terms of energy efficiency and costs. In the third millennium, enabling more careful treatment of heat-sensitive materials such as food products will be an increasingly important role fulfilled by heat pump dryers.

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ARTICLE DE SYNTHÈSE

nombre SMER, la différence entre les conceptions adiabatique et non adiabatique ne sont pas importantes. Ceci est dû au COP similaire et au rendement identique.18

Le séchage ainsi que les applications frigorifiques, seront des méthodes de conservation importantes pour des produits alimentaires au cours du 3e millénaire, étant donné l'augmentation de la population et la demande croissante pour les produits alimentaires préparés. Les séchoirs à pompes à chaleur représenteront à eux seuls une technologie pour le séchage des produits sensibles à la chaleur conçue pour mieux prendre soin et améliorer la qualité du produit séché. La conception d'installations énergétiquement efficaces et sans effet nocif sur l'environnement peuvent être réalisées en respectant les critères de conception ci-dessus, la conception non adiabatique et les frigorigènes naturels. Dans les années à venir, on devrait effectuer des recherches sur la conception des composants, les systèmes et les procédés des installations comprenant des pompes à chaleur en application séchage. La prétransformation et la manutention des matières premières et des produits séchés devraient également faire l'objet d'études. On devrait aussi effectuer des recherches sur les caractéristiques thermiques, de sorption et rhéologiques des matières premières et des produits séchés.

III. CONCLUSION

Afin de remplacer et de réduire le recours aux gaz qui appauvrirent l'ozone et des gaz à effet de serre, l'industrie froid, du conditionnement d'air et des pompes à chaleur et la société doivent trouver de nouvelles réponses et de nouvelles technologies. Cette recherche des solutions a donné lieu à une mutation technologique de grande envergure. Afin d'atteindre notre objectif commun, il va falloir travailler encore beaucoup la question, et nous aurons besoin de tous les talents et l'imagination des gens de toutes les unités de recherche et de développement des universités, des instituts de recherche et de l'industrie. Le défi principal dans l'application des fluides actifs naturels est de développer des systèmes sûrs et fiables capables de concurrencer des systèmes classiques utilisant des HFC en termes d'efficacité énergétique et de coût. Au cours du troisième millénaire, le traitement des produits sensibles à la chaleur (par exemple des produits alimentaires) avec davantage de soin sera de plus en plus le rôle des systèmes de séchage à pompes à chaleur.

![Diagram](Image)

**Figure 1. Flow circuit of a reversible CO₂ heat pump**

_Circuit d'une pompe à chaleur réversible utilisant du CO₂_
Figure 2. Measured COP, cooling mode. Ambient temperatures: 28°C, 35°C and 46°C for AC1, AC2 and AC3 respectively. COP mesuré en mode refroidissement. Les températures ambiante sont : 28 °C, 35 °C et 46 °C, pour les installations de conditionnement d'air AC1, AC2 et AC3, respectivement.

Figure 3. Measured COP, heating mode. Ambient temperatures: 2°C, 7°C and 14°C for HP1, HP2 and HP3 respectively. COP mesuré en mode chauffage. Les températures ambiante sont : 2 °C, 7 °C et 14 °C, pour les pompes à chaleur HP1, HP2 et HP3, respectivement.

Figure 4. Ts diagram showing the transcritical CO₂ cycles used for water heating. Diagramme Ts qui montre les cycles transcritiques du CO₂ en application chauffage d'eau sanitaire.
**Figure 2.** Measured COP, cooling mode. Ambient temperatures: 28°C, 35°C et 46°C for AC1, AC2 and AC3 respectively

*COP mesuré en mode refroidissement. Les températures ambiante sont : 28 °C, 35 °C et 46 °C, pour les installations de conditionnement d'air AC1, AC2 et AC3, respectivement*

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**Figure 4.** Ts diagram showing the transcritical CO₂ cycles used for water heating

*Diagramme Ts qui montre les cycles transcritiques du CO₂ en application chauffage d'eau sanitaire*
Figure 5. COP of the heat pump according to evaporation temperature
*COP de la pompe à chaleur en fonction de la température d'évaporation*

Figure 6. Distributed CO₂ supermarket refrigeration system with central heat recovery
*Système frigorifique d'un supermarché utilisant du CO₂, avec récupération de chaleur centrale*
Figure 7. Total Equivalent Warming Impact (TEWI) for R134a and CO₂ (R744) automobile air-conditioning systems, based on measured power consumption of actual systems. TEWI de systèmes de conditionnement d'air automobiles au R134a et au CO₂ (R744), fondé sur la consommation d'énergie réelle des systèmes.

Figure 8. Section of compact heat exchanger for CO₂ based on extruded micro-channel heat transfer tubes, folded fins, and a "double-barrel" high-pressure manifold design. Section d'un échangeur de chaleur compact au CO₂, muni de tubes de transfert de chaleur extrudés à microcanaux, d'ailettes pliées et d'un double collecteur sous haute pression.
**Figure 9.** Adiabatic and non-adiabatic dryer design

*Conception de séchoirs adiabatique et non adiabatique*

**Figure 10.** Flow sheet of the 2-stage non-adiabatic NH₃ heat pump fluidized bed dryer

*Schéma de la pompe à chaleur à ammoniac bi-étagée non adiabatique, à lit fluidisé utilisée dans les applications de séchage*