HEAT PUMPING SYSTEMS FOR THE NEXT CENTURY

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ABSTRACT

The discovery that the CFCs and the HCFCs could have negative impacts on both the stratospheric ozone layer and global warming has put the mechanical refrigeration industry amidst a new technological shift. New solutions and new technology are required since the CFCs and the HCFCs already are, and will be outlawed, respectively.

The current paper identifies two fundamentally different strategies in coping with this challenge. The first is the *chemical strategy*, which implies developing new synthetic chemicals for conventional types of machinery. The second, the *natural strategy*, is to start with a safe fluid and then develop and design a new piece of machinery fitting that fluid.

Further, the paper discusses research and development efforts within several heat pumping application areas where natural working fluids have been successfully applied in NTNU-SINTEFs laboratories. Specifically, residential air conditioning systems, heat pump water heaters, commercial refrigeration units, automobile air conditioning and heating systems, and heat pump systems for drying of heat sensitive materials have been investigated. The results presented are encouraging, and confirm that the heat pumping industry in the future can be effectively and efficiently served by the use of natural working fluids. Still however, some more development work is needed.

1. INTRODUCTION - HEAT PUMPING TECHNOLOGIES AND FUTURE STRATEGIES

1.1 On Technological Shifts

The mechanical refrigeration industry has experienced several technological shifts throughout its history [Bredesen et al., 1999] The compression-evaporation process, invented by Evans and Perkins between 1805 and 1834, has played an important role for the development of the "heat pumping" industry.

Discovered in 1744, ammonia showed outstanding properties as working fluid. The first successful application came in an absorption plant, developed and patented in 1859 by Ferdinand Carré. The reason ammonia was used with the 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 (CO_2) 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 the starting point of the widespread use of CO_2 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 from 1893 to 1907. From about 1930 they were put into large-scale production.

This development changed the world of refrigeration. By substituting hydrogen with different halogens, like 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. no danger of explosion or panicky smell during leakage. They were easier to handle and they were 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 carbon dioxide (80%) and ammonia (20%) [Stera, 1992]. During the next 50 years, R-22 almost completely took over. In large-scale industrial applications on land, however, ammonia has maintained its position, owing to efficiency and cost reasons.

Another technological shift was the development of the driving motors, making it possible to increase speed and reduce compressor size drastically. Speeds between 1500 to 1750 rpms became common around the Second World War. When the CFCs and HCFCs entered the scene around 1930-40, it became possible also to develop hermetic compressors, and this pawed 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 led to increased quality of life to people around the world. These changes were made possible by innovations creating enormous markets for new product, and thus, industrial opportunities.

Today we are again amidst 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, i.e. *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 Agreement, which 10 years later was established to reduce emissions of global warming gases. In order to be able to phase out the use of ozone depleting and global warming substances, several players must be actively involved (Table 1):

Table 1: Actors and their contributions in a technological shift.

Players	Bringing forward - providing
Universities	New knowledge and new candidates
Research institutes	New technology
Manufacturers	New products
Engineering companies	New solutions
End users	New demands
Governments	New policies

The job of eliminating CFCs in the area of refrigeration, air conditioning and heat pumps is also a much bigger operation than most people outside the industry are aware of. It is estimated that the value of CFC-dependent equipment in the world is in the order of US$200 billion, and that units and plants may be counted in hundreds of millions [Frivik, 1995].

1.2 Strategies for Future Development

The first years after the 1987 Montreal Protocol were characterized by uncertainty in the international heat pumping industry. Now, however, the international community seems to agree on two main strategies, in the process of bringing forward a robust, long-term, and clean heat pumping technology: the "chemical" strategy and the "natural" strategy (Table 2).

Table 2: Differences between the main strategies.

MAIN ISSUES	"CHEMICAL" STRATEGY	"NATURAL" STRATEGY
Precondition	Use standard Evans-Perkins cycle from 1834 (1805) and standard pressure-limits.	Use naturally and ecologically Safe fluids as refrigerants.
Development task	Find new synthesized fluids to fit the standard Evans-Perkins cycle.	Adapt thermodynamic cycle and equipment to fluid and condition of the application.
Goals	Obtain efficiency and safety equal to, or higher, than of present (CFC) systems.	
Environmental Characteristics	Both known negative environmental effects (GWP) and possibly unforeseen consequences.	All uncertainties are eliminated. No unforeseen environmental effects.

The *chemical strategy* is to develop new, complex, synthetic working fluids without ozone-depleting effect. The new class working fluids - the HFCs – are largely compatible with the CFCs and HCFCs so that they may be used in just about the same type of equipment as before. This is an important advantage. At the moment, the most important alternative refrigerants both for new and retrofit applications are the HFCs, but they have been introduced at a far slower rate than expected. On the downside, this strategy promotes substances that are foreign to nature, and that may include a risk of unforeseen global environment effects. It should be kept in mind that it took roughly 50 years before we discovered the flaws of the CFCs/HCFCs. Have we remembered to ask all the relevant questions this time? If not, how long time will it take, and will the answer dictate another phase-out? The HFCs are already known as strong greenhouse gases and are, therefore, included in the basket of substances regulated by the Kyoto Agreement. In any case, it must be preferable to use working fluids that are not being banned basically before they reach the market.

The *natural strategy* deals with using substances that are naturally present in our biosphere, and then develop processes and equipment for these fluids. Such natural fluids include atmospheric gases (air, nitrogen, carbon dioxide, and noble 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. Technology development and improved safety measures have reduced safety hazards and improved public acceptability. The number of hydrocarbon heat pumps is still limited, but they are expected to play an increasingly important role during the next years in small and medium capacity heat pumps. The argument against the natural fluids are that some are flammable, others are toxic, their energy efficiency in traditional cycles may be lower than the fluids that they replace, others again have higher than normal working pressures. These challenges, however, can be dealt with in an effective manner!

It should be emphasized that society depends on both strategies to reach the goals of the international agreements. We need the chemical industry to find solutions to our short and medium term needs. We could never have started the CFC reduction without the HFCs. We also need the natural strategy, although in some cases, longer time for bringing forward the new equipment may be needed. On the other side, this will yield robust and long-term solutions. Therefore, we believe that the next century will be the century of natural working fluids. Further in this paper are presented some examples of important heat pumping technologies where natural working fluids are applied with success.

2. APPLICATIONS WITH NATURAL WORKING FLUIDS

2.1 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 type or of the ductless split type, and usually service a room or two. 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.

The overall market for residential air conditioning systems was in 1997, 34 million units (shipment), 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, and China: 5.5 million. It is estimated that the world market in 2000 will be somewhere between 36 and 38 million units [Ishida, 1998].

The majority of RACs and PACs installed still operate with R-22. During the last couple of years, however, units with R-407C and R-410A 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 successfully been used, but compared to the overall world market size, the numbers are low. As an alternative to the HFCs, CO_2 as working fluid has caught the attention of several manufacturers and research institutions.

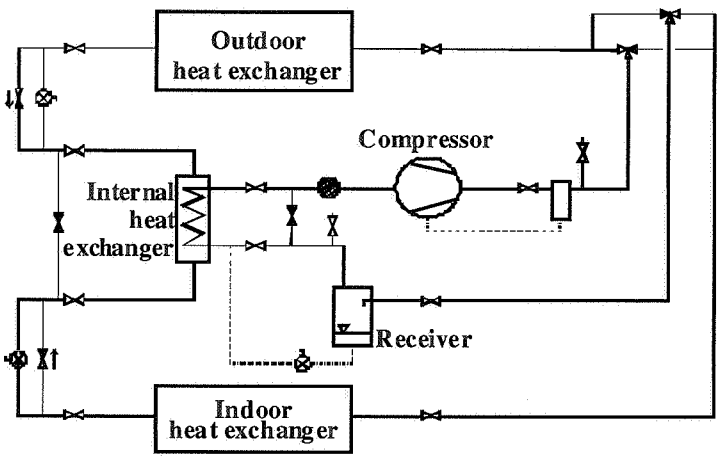

Figure 1: Flow circuit of a reversible CO_2 heat pump [Aarlien and Frivik, 1998].

A detailed simulation study on the performance of R-22 and CO_2 in residential heat pumps gave quite promising results [Pettersen, Aarlien, et. al., 1997]. Figure 1 shows the flow circuit.

To verify the theoretical results, an R-22 unit and a prototype CO_2 system was set up in the SINTEF laboratory. The main results from the experiments are shown in Figures 2 and 3. In AC mode, the COP values of the CO_2 unit are slightly *lower* compared to the R-22 unit. In HP mode, the COP of the CO_2 unit is slightly *higher* compared to the R-22 unit [Aarlien and Frivik, 1998].

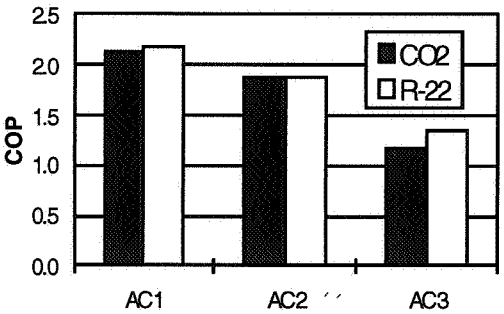

Figure 2: Measured COP, cooling mode. Ambient temperatures are 28°C, 35°C, and 46°C for AC1, AC2, and AC3, respectively.

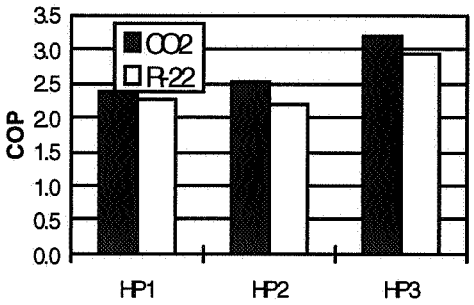

Figure 3: Measured COP, heating mode. Ambient temperatures are 2°C, 7°C, and 14°C for HP1, HP2, and HP3, respectively.

In conclusion, the system efficiency (COP) of the CO_2 system is already competitive to that of the R-22 system in both modes of operation. The CO_2 heat exchanger design concept applied is neither optimal 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 CO_2 compressor has not performed optimally in some of the experiments, owing to worn out bearings, and leakage through the shaft seal. It should also be kept in mind that all of the components used in the plant have been developed for mobile air conditioning, rather than for RACs/PACs. It should be mentioned that it is not the absolute COP level, rather the difference between in COP between CO_2 and R-22 that is important. Based on the above, there should be room for further improvements in the performance of the CO_2 system.

2.2 Heat Pump Water Heaters

CO_2 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 goes to water heating [IEA-HPC, 1993]. In addition, there is a substantial need for water heating in industry, where often the tap water heating may be combined with refrigeration and/or freezing, by utilizing the cold side of the system.

Nekså, Rekstad et al. [1998] and Nekså, Rekstad et al. [1999] describe experimental results from a CO_2 HPWH system. The results show that CO_2 is very well suited as working fluid for tap water heat pumps. The energy consumption can be reduced by 75% compared to electrical or gas fired units, when hot tap water is supplied at 60°C, with the ambient air as heat source. Figure 4 shows the flow circuit and the process in the TS-diagram. Figure 5 shows measured hp-COP as function of the evaporation temperature. The tap water is heated from 8 to 60°C, typical Norwegian conditions. Hp-COP is defined as the heat output divided by the electric power input to the compressor motor.

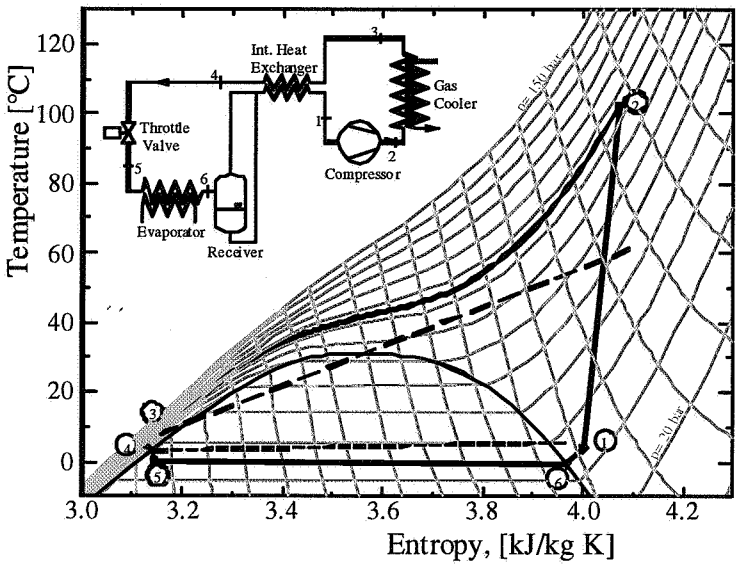

Figure 4: T s-diagram showing the transcritical CO_2 cycle used for water heating.

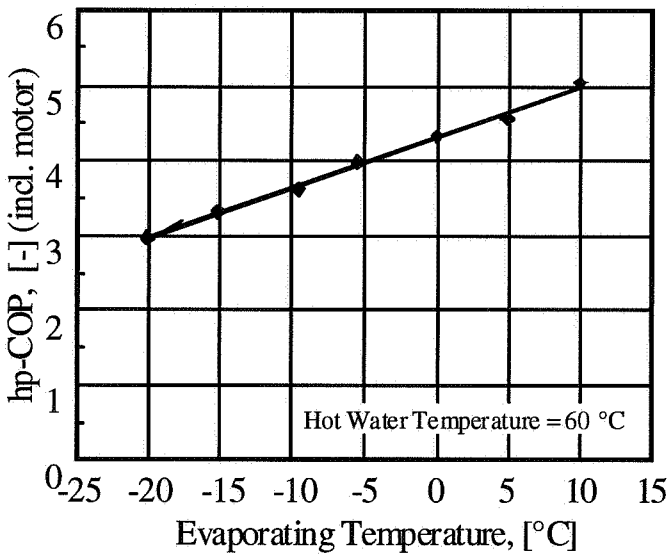

Figure 5: COP for the heat pump when varying the evaporation temperature.

2.3 Commercial Refrigeration

Commercial refrigeration is another application area with a large market potential, and where refrigerant emission is a problem. Nekså, Girotto et al. [1998], describe the possibility of using CO_2 as the only refrigerant in a system with heat recovery. The supermarket refrigeration concept is based on self-contained display cabinets with CO_2 refrigeration units. Figure 6 is a sketch of the system.

The refrigeration units placed in each cabinet reject heat to a waste heat recovery loop. Utilizing the transcritical CO_2 process, it is possible to have a large temperature glide in the loop, typically 50-60 K, and a correspondingly low volume flow rate. Waste heat with high temperature (70-75°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_2 system and a conventional R-22 system with respect to the overall energy consumption of the supermarket for one year of operation in a southern European climate was carried out. The CO_2 system was found to reduce the energy consumption by 32% compared to the R-22 system.

The CO_2 units can also be equipped with a condensing unit in order to reject the heat directly to the shopping area when space heating is required. In the warm season with a heat surplus, the waste heat recovery loop is used to remove the heat. This concept reduces the power demand for the refrigeration units to the same level as for the baseline R-22 system, and the resulting overall energy consumption of the supermarket will then be further reduced.

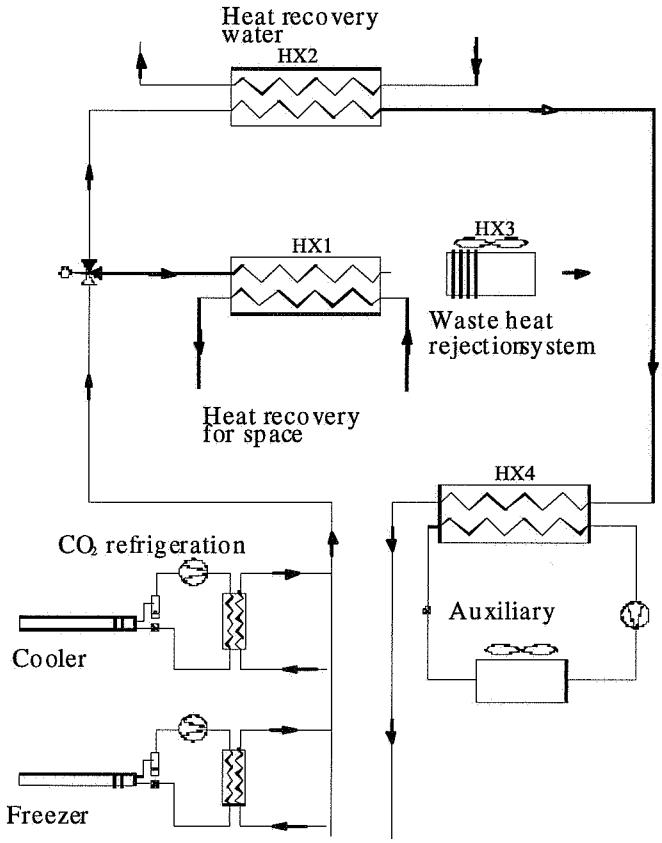

Figure 6: Distributed CO_2 supermarket refrigeration system with central heat recovery.

2.4 CO_2 Automobile Air Conditioning and Heating System

Between 25 and 30 million new automobile air conditioning systems are produced every year [UNEP, 1994], to be installed as a standard feature in more than 50% of all new vehicles. Refrigerant emissions per system have been reduced as a result of technical changes in the transition from R-12 to R-134a, but automobile air conditioning is still the dominating source of R-134a emissions to the atmosphere. Almost all of the 84.000 metric tons of R-134a produced in 1996 [AFEAS, 1999] was targeted for 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 [1992] reported the first experimental results on a prototype CO_2 system for automobile air conditioning. A comparison was made between a state-of-the-art R-12 system and a laboratory prototype CO_2 system with equal heat exchanger dimensions and rating point capacity. Although simple cycle calculations indicated that the CO_2 system efficiency would be inferior, a number of practical factors made the actual efficiencies of the two systems equal. Thus, the conclusion in 1992 was that a competitive system could be realized based on a non-toxic, non-flammable, zero-ODP, and zero-GWP refrigerant.

The CO_2 system operates in a transcritical cycle, i.e. with supercritical high-side pressure. Owing to the low pressure-ratio in this cycle, the 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 plays a significant role for the system COP, since the throttling loss is greatly reduced by lowering the minimum heat rejection temperature.

Earlier studies on TEWI of automobile air conditioning systems were based on modeled COP data only. Yin, Pettersen et al. [1999] published TEWI data based on measured power consumption for a state-of-the-art R-134a system and a prototype CO_2 system. The results show that the CO_2 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.

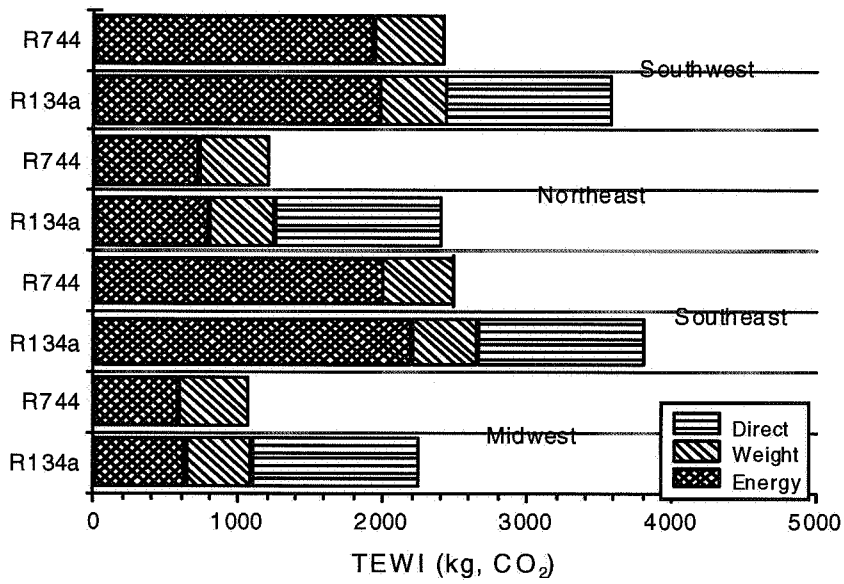

Figure 7: Total Equivalent Warming Impact (TEWI) for R-134a and CO_2 (R744) automobile air conditioning systems, based on measured power consumption of actual systems [Yin and Pettersen, 1999].

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. [1998] reported results for compact and lightweight heat exchangers adapted to CO_2. 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.

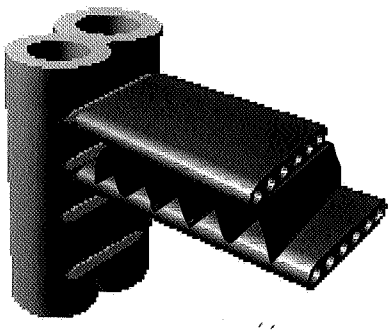

Figure 8: Section of compact heat exchanger for CO_2 based on extruded micro-channel heat transfer tubes, folded fins, and a "double-barrel" high-pressure manifold design [Pettersen et al., 1998].

Modern cars with fuel injection engines often have insufficient waste heat for heating of the passenger compartment in the winter season. The prolonged heating-up period and slow defroster action is 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. Carbon dioxide 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. [1998] proposed an advanced circuit for reversible cooling and heating.

2.5 Heat Pumps for Drying of Heat Sensitive Materials

Drying operations typically represents 10-15% of the industrial energy consumption in developed countries [Baker and Reay, 1982]. Heat pumps have found their industrial applications in drying of materials of biological origin. The dominating application of industrial heat pumps is found within drying of different types of food products and wood. Heat pump dryers have several advantages compared to oil/gas heated systems and natural drying:

- Improved product quality due to a lower drying temperature and independence of ambient air conditions, including problems with insects and birds. In addition to improved quality this will also give a better utilization of raw materials and reduced spoilage.
- Reduced energy consumption due to the COP of the heat pump of 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 the dryer design and operation.
- Heat pump dryers represents an 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; $COP=Q_0/W$ (-), whereas the SMER number (Specific Moisture Extraction Rate) 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. To achieve as high a SMER number as 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.
- As high an inlet temperature in the dryer as possible, due to improved thermal efficiency and capacity.
- As low a refrigeration capacity as possible, as long as the desired production is achieved (over-sizing will increase dh/dx and reduce SMER).
- The choice of evaporating and condensing temperature of the heat pump should be the combination giving the best combination of COP and dh/dx (an optimum might exist)

Industrial dryers used today are of 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 give a considerable increase in the dryer capacity. Adiabatic and non-adiabatic (isothermal) drying are shown in the humid air diagram in Figure 9.

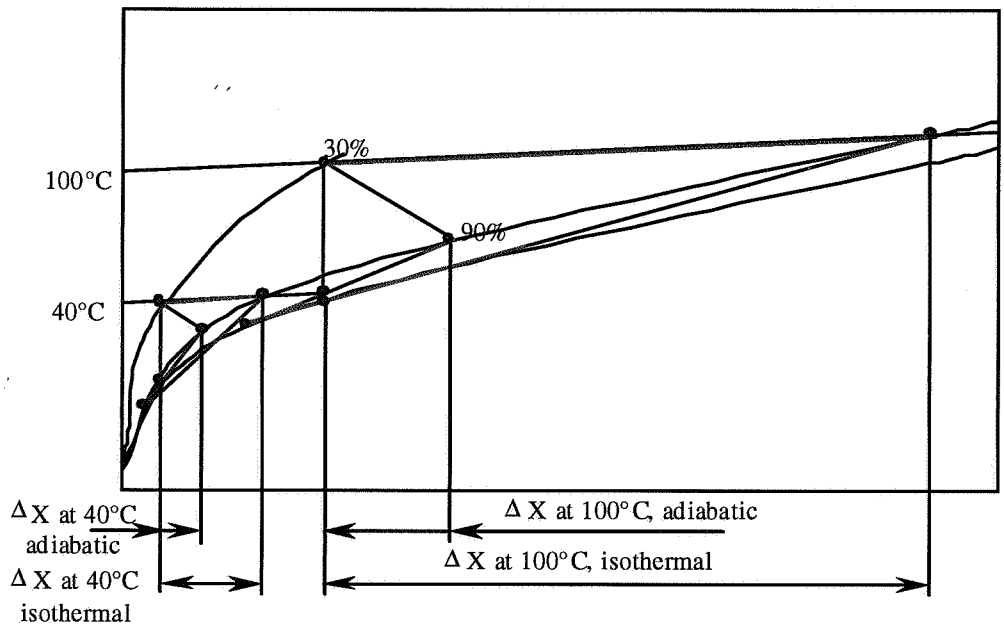

Figure 9: Adiabatic and non-adiabatic dryer design.

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 drier was designed to have as high a SMER number, and as high capacity as possible.

The above mentioned design criteria for heat pump dryers were followed in this plant. Results from continuous drying experiments show SMER numbers of up to 4.7 kg water/kWh, and increase in the drying capacity (compared to adiabatic drying) of 380%. A non-adiabatic design will, therefore, be more compact and with a lower investment than an adiabatic design. With respect to the SMER number there is no big difference between adiabatic and non-adiabatic design. This is due to approximately the same COP and also the same thermal efficiency [Jonassen and Strømmen, 1994].

Drying will together with refrigeration be important preservation methods for food products in the next millennium due to increased population and the increased need for ready-to-eat food. Heat pump dryers will be one actual technology for 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 realized through following the design rules listed above and using non-adiabatic design and natural refrigerants. In the coming years research should be done on component, system and process design on the heat pump and the drying unit. Also pre-processing and handling of raw materials and dried product should be scrutinized. Further research should also be done on thermal, sorption and rheological characteristics of the raw materials and dried product.

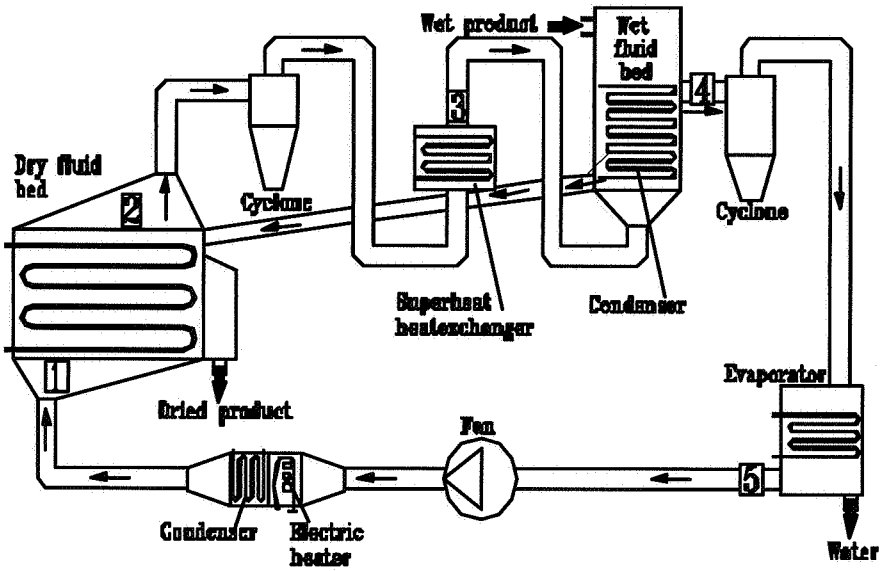

Figure 10: Flow sheet of the 2-stage, non-adiabatic NH_3 heat pump fluidized bed dryer.

3. CONCLUSION

To phase out and reduce the ozone depleting and global warming gases, the heat pumping industry and society need new solutions and new technology. This has started a large technological shift. To reach our common goal, a lot of hard work is needed, and we have to utilize the skills and imagination of all the enthusiastic research and development groups in universities, research institutes, and industry. The main challenge when applying natural working fluids are to build safe and reliable systems that are able to compete with conventional HFC system regarding energy efficiency and costs. To take better care of heat sensitive materials, like food products, heat pump dryers will play an increasingly important role in the next millennium.

This paper has presented some important applications of natural working fluids. Within automobile air conditioning, residential air conditioning, heat pump water heating, commercial refrigeration, and drying, heat pumping systems can be realized with a high energy efficiency and lower TEWI compared to HFC systems. In this strategy the working fluid is available and also at a low cost. However, more development work is needed on the process and equipment side.

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SYSTEMES FRIGORIFIQUES ET DE POMPE A CHALEUR POUR LE SIECLE A VENIR

RÉSUMÉ: La découverte que les CFC et les HCFC pourraient avoir des impacts négatifs sur l'ozone stratosphérique et le réchauffement planétaire a conduit l'industrie du froid mécanique vers un nouveau changement technologique. De nouvelles solutions et de nouvelles technologies sont exigées puisque les CFC sont déjà proscrits, et les HCFC le seront prochainement.

Cet article présente deux stratégies fondamentalement différentes afin de faire face au défi. La première est la *stratégie chimique*, qui implique le développement de nouveaux produits chimiques pour les machines courantes. La seconde, la *stratégie naturelle*, voit l'utilisation d'un fluide sûr puis le développement et la conception d'une nouvelle machine appropriée pour ce fluide.

En outre, cet article aborde les efforts entrepris en recherche et développement dans plusieurs domaines d'application du froid et des pompes à chaleur où des fluides naturels ont été utilisés avec succès dans les laboratoires de NTNU-SINTEF. De manière plus précise, les dispositifs de climatisation résidentiels, les chauffe-eau fonctionnant avec des pompes à chaleur, les unités commerciales frigorifiques, les systèmes de climatisation et de chauffage de véhicules, et les systèmes de pompe à chaleur pour le séchage des matériaux sensibles à la chaleur ont été examinés. Les résultats présentés sont encourageants, et confirment qu'à l'avenir, les fluides naturels pourront être utilisés de manière efficace et pertinente dans les applications frigorifiques et de pompes à chaleur. Cependant, davantage de travail de développement reste nécessaire.