Energy efficient and environmental friendly heat pumping system using CO_2 as working fluid
COHEPS

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Contract N^o: JOE3-CT95-0006

PUBLISHABLE FINAL REPORT

February 1996 to January 1999

Research funded in part by
THE EUROPEAN COMMISSION
in the framework of the
Non Nuclear Energy Programme
JOULE III

1 Content

2 Abstract

The "natural" refrigerant CO_2 is an old refrigerant (Linde 1881) and has been used in the past for maritime cooling and for air conditioning systems in buildings, until it was replaced by the (H)CFCs.

Taking the old "natural" fluids, only water (R-717) and CO_2 (R-744) meet the requirements according EU regulation of December 1994. The limitations of water are the freezing temperature of 0°C and the low volumetric capacity at temperatures below 100°C; the limitations of CO_2 have so far been the critical data, i.e. 31°C at 70 bar.

For heat pumps with condensing temperatures exceeding 30°C, the trans-critical cycle with pressures up to 150 bar as proposed by G. Lorentzen has to be used. This trans-critical CO_2 cycle offers a completely new characteristic: The "Lorentzen-cycle" has its favorable application in the case of an unlimited heat source and a limited heat sink with high temperature glides.

Prototypes were developed, constructed and analized as test rigs from several partners for following applications:

- hot water heat pumps for residential applications [TUGRAZ.IFW]
- commercial heat pumps for water heating and heat recovery [SINTEF.RAC]
- heat pumps for space heating for retrofitting existing high-temperature systems [FKW]
- heat pumps for dehumidification and drying processes in residential and commercial applications [UESSEN.ATK].

Rather all results could fulfill the topics expected in the proposal to this poject and the fits between modelling and test analysises was extremely high. This is very promising in order to continue in CO2 technologies and to make further efforts for demonstration and dissemination of the resluts of this research project.

Only one not so successful topic occured. Compressors could be used for test rig installations from two manufactures (in Germany and Denmark). These comressors were prototypes and not produced within a mass manufacturing. An Italian manufacturer presented a new design at

the CO2 work shop in Mainz, March 1999, which will offer new possibilities for the next steps in development and dissemination.

Design guide lines were developed for different applications by the responsible partners. These give a condensed overview about the essential topics, which have to be treated by further development and construction of CO2 heat pumping systems.

Conclusions resulting from extended analysis are, that the risks related to the use of CO_2 in heat pumps are low and acceptable if the charge is limited such that concentrations in rooms after release of the charge are less than some 5%.

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4 Objectives

The "natural" refrigerant CO_2 is an old refrigerant (Linde 1881) and has been used in the past for maritime cooling and for air conditioning systems in buildings, until it was replaced by the (H)CFCs.

Based on Copenhagen 1992 and the EU regulation of December 1994, CFCs and HCFCs have to be phased out. At present time many Fluor Carbons (FC`s, i.e. R 134a) and some Blends (i.e. R 407 C, R410A) are in the phase of market penetration, also some Flammables (i.e. R 290) and Ammonia are coming back. But none of these will meet the requirements of safety refrigerants:

non toxic,
non flammable,
no ODP and
no GWP.

Taking the old "natural" fluids, only water (R-717) and CO_2 (R-744) meet these requirements. The limitations of water are the freezing temperature of 0°C and the low volumetric capacity at temperatures below 100°C; the limitations of CO_2 have so far been the critical data, i.e. 31°C at 70 bar.

Presently CO_2 is reinvented for low-temperature applications in refrigeration systems. For heat pumps with condensing temperatures exceeding 30°C, the trans-critical cycle with pressures up to 150 bar as proposed by G. Lorentzen has to be used.

This trans-critical CO_2 cycle offers a completely new characteristic: While the Carnot cycle - most commonly utilized in vapor-compression systems - is suitable best for an unlimited heat source and heat sink, and the Lorenz and the Joule cycle for a limited heat source and heat sink with high temperature glides, the "Lorentzen-cycle" has its favorable application in the case of an unlimited heat source and a limited heat sink with high temperature glides. Ideal applications of this cycle are all processes, where the condenser inlet has a low temperature level - near the evaporating temperature - and the condenser outlet temperature required is high. This is most commonly the situation for heat pump applications in the case of hot water

production, in air heating systems, in many systems for waste heat recovery and for drying and dehumidifying applications.
Utilizing this trans-critical CO_2 cycle it should be possible to retrofit conventional boilers by heat pumps, and it is also possible to use this cycle for charging existing hot water storage tanks with once-through water heaters; the existing market potential is tremendous.

However, the large market in Europe is the market of existing buildings equipped with conventional heating and hot water systems, in the case of heating most commonly hydronic systems with high-temperature heat distribution systems, in the case of hot water production central systems with high-temperature storage tanks. Considering the large number of systems in operation, it seems to be necessary to find a solution to replace fossil fuel fired systems by alternative heat generating systems suitable for high supply temperatures. With heat pump cycles most commonly used this goal can only be achieved by using bivalent systems or by insulation the building and increasing the heat transfer area installed.
The trans-critical CO_2 cycle offers the possibility of retrofitting these existing buildings in an energy efficient way using an environmentally benign refrigerant, a substance which has always played an important role in our biosphere.

Due to the environmentally friendly behavior, which is guaranted by the refrigerant itself, safety aspects and energy efficiency will lead to wide spreaded applications with an unlimited heat source at constant temperature and a limited heat sink with a large temperature glide.

Results of theoretical and experimental investigations shall be transferred into prototype development and prototype testing for the applications:

hot water heat pumps for residential applications
commercial heat pumps for water heating and heat recovery
heat pumps for space heating for retrofitting existing high-temperature systems
heat pumps for dehumidification and drying processes in residential and commercial applications.

The transcritical CO_2-cycle and the components needed to realize it, are different from common technology. Research and technology development work shall be carried out to analyze the characteristics of the cycle and to develop new components.

This development have to be concentrated on high-pressure equipment, especially compressors, expansion devices and heat exchangers. New control strategies have to be developed and tested, special cycle dynamics investigations have to be carried out.

The pressures required by this cycle significantly exceed the 30 bar technology most commonly used in heat pumping technologies. However, hydraulic equipment also operates with pressures of 200 bar with peaks up to 400 bar: this means the technology is available and proven as safe.

The heat pumps developed shall lead to energy savings and to a reduction of the emission levels of greenhouse gases compared with usual heat generating systems based on fossil fuels. It shall be superior to existing heat pumps because the working fluid CO_2 is both safe (not toxic, not flammable) and environmentally benign (no ODP and no GWP in this application). In addition, the heat pump using the transcritical CO_2 cycle is, in contrast to common heat pumps, applicable even for high outlet temperatures without a significant loss in efficiency.

Design guidlines for heat pumping system with the "natural" fluid CO_2 as working fluid shall be developed and will be a basis for further investigations, demonstrations and disseminations of the results (research and testing) within the Fifth Framwork Programme of the Commission.

The advantages are:

Environmentally friendly behavior is guaranteed by the refrigerant itself. CO_2 is a safety refrigerant (not toxic and not flammable) and environmentally benign (no ODP, no GWP, no dangerous decomposition products).

Energy efficiency can be achieved by utilizing the unique characteristics of the new trans-critical cycle.

In the case of an unlimited heat source and a high temperature glide at the heat sink side, starting with a temperature similar to the heat source temperature, this cycle has no competitor if compared with cycles already in use.

5 Technical Description and Results of the Project COHEPS

1. Work Packages

According to the Technical Annexe the total task of the project was divided into twelve Work Packages(WP) with differant participants per package. The several Work Packages were handling with exactly separated and fixed sections of the COHEPS-project.

The content of the Work Packages was covered by the partners

- Si: SINTEF Refrigeration and Air Conditioning, NO,
- Fk: FKW, DE,
- Es: University Essen, DE,
- Le: University Leuven, BE,
- Gr: Graz University of Technology, AT,

as follows:

W P	Work Package	Si	Fk	Es	Le	Gr
1	Thermodynamic and transport properties				x	x
2	Cycle calculations	x	x	x		x
3	Application studies	x		x	x	x
4	Compressor		x			
5	Heat transfer and pressure drop data				x	x
6	Heat exchanger development		x			x
7	Expansion device		x			
8	Control system	x	x	x		x
9	Safety			x	x	
10	Cycle dynamics	x	x	x		x
11	Prototype system design and construction	x	x	x		x
12	Prototype system testing	x	x	x		x

x Subcoordinator for Work Package

Final Reports for each Work Package contain the detailed and extended results of the resarch activities, prototype design, construction and testing.

2. Applications

The results of theoretical and experimental investigations have been transferred into prototype development and prototype testing for following applications by several partners:

- hot water heat pumps for residential applications: Graz University of Technology, AT

- commercial heat pumps for water heating and heat recovery: SINTEF Refrigeration and Air Conditioning, NO
- heat pumps for space heating for retrofitting existing high-temperature systems: FKW, DE
- heat pumps for dehumidification and drying processes in residential and commercial applications: University Essen, DE.

The investigations concerning “Thermodynamic Properties”, “Heat Transfer and “Pressure Drop Data” and “Risk Analyses” are used as overall necessary basic input for each application.
The following capters describe the basic results and the essential topics for several applications (Abstracts and Conclusions).

Detailed explanations were presented at the CO2 Work Shop in Mainz, March 1999, where the results of the COHEPS-Project were presented to the *European Community of CO_2-Heat Pumping Technologie* . This work shop was partly organized as the official final activity within the COHEPS-project.

2.1 CO_2 Properties

René Rieberer, SINTEF Energy Research, N-7465 Trondheim [1]

Abstract

CO_2 (R-744) is a safety refrigerant without Ozone Depletion Potential and negligible Global Warming Potential. The thermodynamic properties of CO_2 are well known, but they are ‘new’ for heat pumps because CO_2 differs considerably from common refrigerants. In heat pumps the critical data of CO_2 (31°C, 74 bar) result in near-critical conditions, i.e. high pressures, densities, and heat transfer coefficients.

Investigations have shown that the heat transfer and pressure drop in single-phase flow can be estimated with ‘standard’ calculation models. In contrast to heat transfer at evaporation which shows still problems: The heat transfer of pure CO_2 can be estimated precisely, but in case of oil-contamination the heat transfer drops significantly and the models overestimate the ‘reality’.

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[1] Former by: Institute of Thermal Engineering, Graz University of Technology, Austria.

Introduction

'Safety refrigerants' have been used as working fluids for heat pumps since the 1930s. Nowadays these refrigerants are called 'ozone killers' and 'greenhouse gases'. These 'safety refrigerants' are artificial substances, they are: chloro-fluoro-carbons (CFCs) and hydro-chloro-fluoro-carbons (HCFCs). While both the CFCs and the HCFCs have a high Global Warming Potential (GWP) the HCFCs have a reduced - but existing - Ozone Depletion Potential (ODP).

According to international agreements, e.g. the 'Protocol on Substances that Deplete the Ozone Layer' of Montreal, September 1987, and its successors, the replacement of the (H)CFCs, i.e. CFCs and HCFCs, as working fluids for heat pumps was agreed. 'New' refrigerants must be found. The late professor Gustav Lorentzen was the person who initiated the development of CO_2 heat pumps. One reason was the discussion concerning the replacement of the (H)CFCs with a new family of related substances, the hydro-fluoro-carbons (HFCs) such as R-134a.

Besides the 'well' known refrigerants ammonia (NH_3, R-717) and propane (C_3H_8, R-290), carbon dioxide (CO_2, R-744) represents a further 'natural' alternative. CO_2 is not a new refrigerant. It was used for air conditioning and refrigeration until the introduction of the (H)CFCs in the 1930s and 1940s. The reasons for phasing out CO_2 were the high working pressure and the decreasing efficiency of the cycle at heat-sink temperatures exceeding 20°C. However, nowadays the properties of CO_2 are new for the heat pump technology. Therefore, the aims of the COHEPS project were the development of a refrigerant database (CO2REF [2]) and the investigation of heat transfer and pressure drop characteristic.

Chapter 2 gives an overview of the most relevant properties and, additionally, a comparison of CO_2 (R-744) with R-12, R-22, R-134a, ammonia (R-717), propane (R-290), and R-410A is presented.

Since operation of a CO_2 heat pump takes place close to the critical point common heat transfer and pressure drop correlations had to be verified .

Conclusions

CO_2 is a 'natural' substance and it is a safety refrigerant without ODP and with negligible GWP. The exact knowledge of the properties - also near the critical point - is necessary for the development of highly efficient components. The properties of CO_2 are well known.

The low critical temperature and the high critical pressure lead to high densities in the temperature region suitable for heat pump applications. For temperatures higher than the critical temperature, the pseudo-critical temperature 'replaces' the saturation temperature. Near this temperature the properties of CO_2 change strongly with temperature.

The properties of CO_2 differ considerably from those of conventional refrigerants like (H)CFCs, HFCs, ammonia, or propane. The high pressure level requires a change from the - in heat pumps presently used - '30 bar- and 40 bar-technology' to a '150 bar-technology'. However, due to the advantageous properties of CO_2, heat pump components become compact.

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[2] CO2REF is mainly based on the work of Stewart (1986) for calculating the thermodynamic properties and on the work of Vesovic (1990) for calculating the transport properties.

The results of the investigations on heat transfer and pressure drop can be summarized as follows:

→ For modeling single-phase flow of CO_2 at trans-critical and sub-critical conditions, the Gnielinski correlation for the heat transfer coefficient and the Colebrook and White correlation for the frictional pressure drop are well suited.

→ Further investigations of the heat transfer of CO_2 at evaporation have to be carried out. Especially the effect of different lubricants in the system has to be studied carefully. The pressure drop at evaporation can be predicted satisfactorily with common models.

Concerning the heat transfer coefficient of CO_2, one has to consider that the design of the heat exchanger is based on the correlation for the overall heat transfer coefficient. It takes into account the heat transfer coefficient of both fluids as well as the heat conductivity of the tube material and a possible heat resistance caused by fouling. Since the heat transfer coefficient of CO_2 is high, and may be higher than the heat transfer coefficient of the other fluid, a precise calculation of the CO_2-side heat transfer coefficient is not very important for practical design.

2.2 Safety Aspects of CO_2 Heat Pumps

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Introduction

The present text is the condensed version of the final report of Work Package 9 : Safety Aspects, of the E.U. research project "Energy Efficient and Environmental Friendly Heat Pump Systems using CO_2 as working fluid (COHEPS)".
Work package 9 was performed by the Katholieke Universiteit Leuven (B). The Universität Gezamthochschule Essen (D) contributed to the analysis of the codes and standards related to CO_2 heat pumps.

The evaluation of safety standards related to heat pumps constitutes the first part of the work package. In the second part a quantitative risk analysis of CO_2 heat pumps is made.

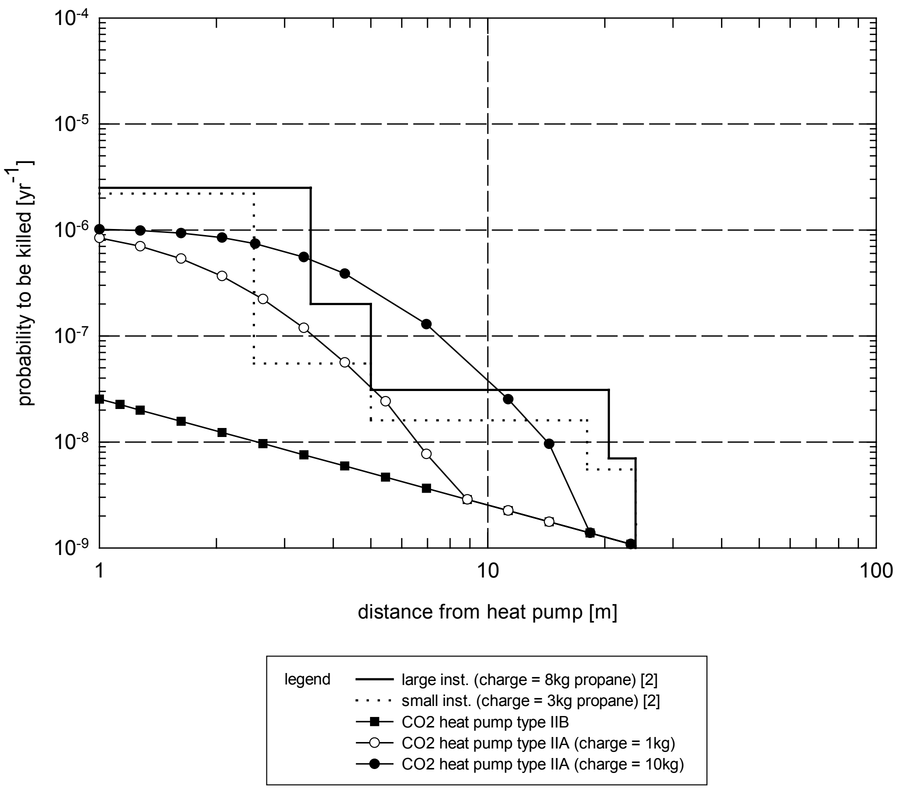
Risk evaluation

It is often stated that the individual risk related to industrial activities should be negligible (say 1%) of the mortality risk for the strongest part of the population. Since the latter is 10^{-4} per year a limit value often used for the individual risk is 10^{-6} per year [10].
Considering this figures show 5 to 8 show that the IA and IB type heat pumps lead to very high individual risks. However in several standards the use of CO_2 heat pumps in rooms with a charge which at rupture gives rise to concentrations larger than 5% is prohibited. If such standards are applied it can be concluded that CO_2 heat pumps give rise to low individual risks.

Comparison

The individual risks identified above can be compared with the risks generated by competing systems or similar systems.
With respect to an alternative heating system one could consider heating by means of natural gas. Statistical observations show that the individual risks connected with the use of natural gas is $1{,}9.10^{-6}$ per year. This is larger than the individual risk for type II heat pumps.

One could also make a comparison with similar systems. This is done in figure 9.



Comparison individual risk CO_2 heat pump and propane mobil refrigeration unit

Here the risks regarding propane refrigeration machines are plotted [10]. Again the CO_2 heat pumps perform better.

A comparison can also be made with R22 heat pumps. In general it is found that for the same application (temperatures) the explosive strength of 1 kg of CO_2 is some 3,5 times larger than that of 1 kg of R22. As a result of this an overpressure of some 40 mbar will be reached at a distance 33% larger for CO_2 than for R22 (for the same mass). This will be reduced by the fact that CO_2 results in smaller heat exchangers than R22, and therefore a smaller CO_2 charge. At any rate the probabilities will not be different for CO_2 or R22, only the impact distances maybe somewhat larger for CO_2.

Conclusions

It can be concluded that the risks related to the use of CO_2 in heat pumps are low and acceptable if the charge is limited such that concentrations in rooms after release of the charge are less than some 5%.

2.3 CO_2 Heat Pumps forResidential Applications

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Abstract
CO_2 is a high-pressure fluid, and for heat pump applications a trans-critical or at least a near-critical process has to be used. In this part of COHEPS residential heat pump water heaters and air heating systems have been investigated.

With heat pump water heaters presently available on the market 60°C cannot be achieved without an auxiliary heating system. CO_2 offers these 60°C highly efficient with COPs of 4 to 5 and without any problems, as long as the once-through characteristic can be kept. The optimum pressure, where the maximum COP can be achieved, is between 90 and 100 bar. The only problem is reheating of water cooled down by insulation and circulation losses. Due to the high heat sink inlet temperature the COP drops significantly.

Low-heating-energy houses are characterized by small transmission losses compared to the ventilation losses. A further reduction of the heat consumption can be achieved by controlled ventilation systems with exhaust air heat recovery by heat pumps or combinations of heat exchangers and heat pumps. Adding a ground collector - concrete tubes buried in the ground around the basement of the building – the total heat load can be covered, SPFs of such systems are about 6.

Conclusions
The investigations presented here show excellent applications for CO_2 heat pumps: The cycle characteristic is fully utilized and heat transfer losses can be kept small. Heat pump water heaters with CO_2 as refrigerant are such a solution, they can be constructed more compact than heat pump water heaters based on the presently used 30 bar technology, and they offer an improved efficiency. Another advantage is that hot water temperatures up to 90°C can be achieved.

The air heating system investigated in this paper is suitable to cover the overall heating demand of a low-heating-energy building. The significant reduction of investment cost by omitting the conventional heating systems offer the installation of such a controlled ventilation system suitable for heating the building without additional cost. The energy efficiency of such systems is extremely high, and additionally, the hygienic situation in the building can be improved significantly. But the system has some more interesting features: it can be used for hot water production during the whole year, and for cooling or at least dehumidification during summertime, in combination with hot water production, even without additional energy.

CO_2 is an excellent refrigerant for such systems: It is a safety refrigerant, which is necessary for direct-evaporation/condensation operation, and it is a natural working fluid without ODP and negligible or zero GWP.

2.4 Commercial Heat Pumps for Water Heating and Heat Recovery

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Abstract

CO_2 is one of the few non-toxic and non-flammable working fluids that do not contribute to ozone depletion or global warming, if leaked to the atmosphere.

Tap water heating is one promising application for a trans-critical CO_2 process. The temperature glide at heat rejection contributes to a very good temperature adaptation when heating tap water, which inherits a large temperature glide. This, together with efficient compression and good heat transfer characteristics of CO_2, makes it possible to design very efficient systems.

A heating-COP of 4.3 is achieved for the prototype when heating tap water from 9 to 60°C, at an evaporation temperature of 0°C. The results lead to a seasonal performance factor of about 4 for an Oslo climate, using ambient air as heat source. Thus, the primary energy consumption can be reduced with more than 75% compared to electrical heating, as commonly used in Norway.

Another significant advantage of this system, compared to conventional heat pump water heaters, is that hot water with temperatures up to 90°C can be produced without operational difficulties.

The market potential for hot water heat pumps is large. 20% of the energy use in residential and commercial buildings is due to water heating.

(Keywords: refrigerant; working fluid; natural; CO_2; trans-critical; heat pump; water heater; prototype; COP; high temperatures)

Conclusions

The experimental results from the heat pump prototype system show that CO_2 is very well suited as working fluid for heat pump water heaters. The energy consumption can be reduced by 75% compared to electrical or gas fired systems, when tap water is heated from 9°C to 60°C, using ambient air as heat source.

The high process efficiency is partly due to good adaptation of the process to the application, but also very efficient compression-process and good heat transfer characteristics for CO_2 are contributing to the high COP.

A CO_2 heat pump water heater may produce hot water with temperatures up to 90°C without operational problems. The area of application is thus much larger than for the traditional heat pump systems, often restricted to hot water temperatures lower than 55°C.

Due to the high volumetric efficiency, leading to small flow areas, and the good heat transfer characteristics of CO_2, it should be possible to produce the systems compact and cost efficient.

The market potential for hot water heat pumps is large. 20% of the energy use in residential and commercial buildings is due to water heating /11/. In addition there is a large need for heating of water in the industry.

2.5 Carbon Dioxide Heat Pumps for High Temperature Hydronic Heating Systems in Existing Buildings

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Introduction

Te motivation for this investigations was that up to now there is no heat pump system available in the market which can really achieve high supply temperatures for hydronic heating systems because of the conventional refrigerant cycles with a maximum pressure of 25 bar. CO_2 with its transcritical cycle as proposed by Gustav Lorenzen [i] offers the possibility of really achieving high temperatures because the refrigerant carbondioxide is much more stable than the hydrofluorocarbons.
Furthermore, the substitutes for the chlorfluorocarbons, the newly developed hydrofluorocarbons show a certain greenhouse warming potential so that, when using CO_2 in small amounts like in heat pumping systems an environmental benefit can be achieved by such a benign working fluid.
The market potential for heat pumps retrofitting old existing high temperature heating systems in buildings is much higher than for new buildings so that there could be a big market potential for such a type of heat pump. For instance in Germany there are about 10 million existing single or two family houses with fossil fuel heating systems whereby each year from that stack around 600.000 systems have to be renewed in comparison only 200.000 new single or two family houses are built in Germany annually.
This number shows the large market potential of retrofit heat pumps which could fulfil the task of high supply temperatures for existing heating systems in old buildings. The typical design of such existing heating systems are either supply and return temperatures of 90/70 °C or 70/50 °C. These temperatures normally cannot be achieved by the currently available heat pumps on the market with either hydrofluorocarbons or hydrocarbons, which allow maximum condensing temperatures of around 60 °C. If a heat pump for retrofitting existing boilers for such systems the main question is that a heat source should readily be available anywhere. Therefore ambient air is the most favoured heat source because it is available anywhere but less favourable than other sources.

Conclusions

Within the EC funded COHEPS - project the natural fluid CO_2 has been investigated as the refrigerant in certain heat pump applications. The main task of *FKW* was developing, designing and building a prototype of an energy efficient and environmentally friendly CO_2 heat pump for application in heating systems of existing buildings. Together with KKW another prototype of a water/water CO_2 heat pump has been built.
After finishing cycle calculations and component selection was finished tests have been carried out with the twp prototypes. *FKW* had tested a air to water heat pump in its climate chamber; KKW had done their measurements on a water (brine) to water heat pump.
Due to the fact, that KKW has used water on the heat source side the heat source temperature and therefore the evaporation temperature was kept almost on the same level. In test of *FKW* an air cooled evaporator was used. For the measurments the evaporation temperature was set 8 K below the ambient temperature.
Concerning the COP *FKW* worked with a pure compressor COP whereas KKW had calculated their COPs including motor and inverter efficiency. Consequently the results could not be compared directly but some key statements for both test sequences could be made.

Controlling the gas cooler pressure to achieve high efficiency for all operation conditions seems to be unnecessary for applications with a nearly constant evaporation temperature. This could be realised through using water or brine on the heat source side. Even on test rigs with an air cooled evaporator only a slightly disadvantage in COP could be seen when operating with an optimum gas cooler pressure.
The results of the test rig at *FKW* with the BOCK compressor have shown some promising results. The results at KKW pointed out some problems. Mainly the combination of motor and inverter of the DANFOSS compressor has to be improved to get better COPs.
Further improvements concerning the compressor have to be made. Efficiency and leakage rate should be objects for future investigations. Heat exchangers and all other parts of the test rig were not optimised in this early state development.
Some components (e.g. an expansion machine for CO_2) are not developed yet. With these components different cycle designs will help to improve the energetic efficiency.

2.6 Heat Pumps for Dehumidification and Drying Processes in Residential and Commercial Applications - Hot Air Drying Heat Pump using a Transcritical CO_2 Process

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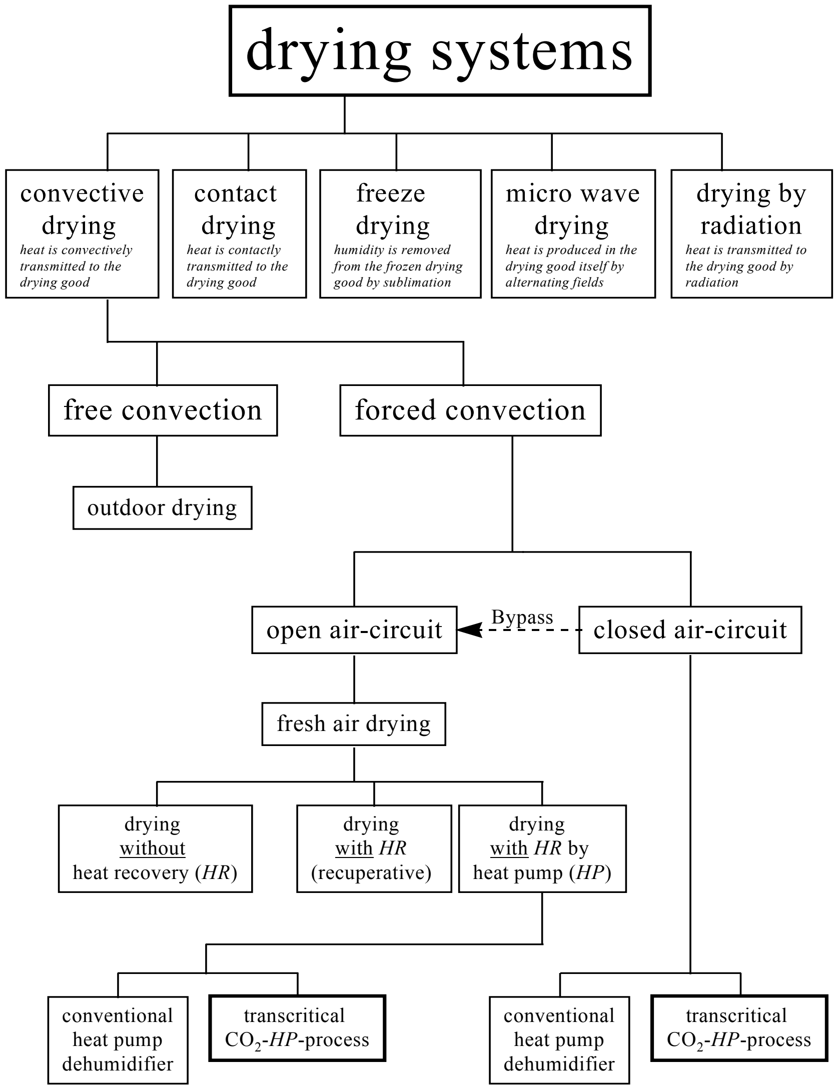
Introduction

Drying in its most general definition is a separation process of a solid matter and a liquid/volatile one, which can be run be mechanical or thermal driving forces.
The drying systems compiled in Fig. 1 represent thermal drying systems. They may be distinguished by the methods of heat supply and their temperature levels, by the methods of heat and mass transfer and by the design of the air circuit, open or closed, with or without heat recovery. A closed air circuit with heat recovery by a heat pump offers a maximum of energy saving potential and of operational advantages.
Under environmental aspects a CO_2 operated heat pump dryer is superior to a dryer equipped with a conventional heat pump, operated with an HFC working fluid, e.g. R134a. Thermal and energetic aspects turn out at least equivalent or even superior, when using a transcritical CO_2 process.



Drying systems

Conclusion

Summing up the experience gathered when calculating, designing, building and testing the prototype device it can be concluded:

1. Calculation and design fundamentals, e.g. thermodynamic and transport properties, as well as heat transfer and pressure drop equations, are developed to a sufficiently high standard.
2. Meeting thermal and energetic design goals is however not only a question of proper calculation but also of extensive tuning of the experimental device. Here the success of first optimising measures gives hope that further essential improvements can still be reached.
3. The usability of the heat pump dryer can only be proven under practical conditions. Precondition for that is a prototype suitable for operation under field test conditions. The present prototype has been designed to optimal experimental accessibility so that the compressor unit, the gas cooler and the fan have been positioned out of the dryer casing.

A second prototype, comprising all components in a casing of usual size and equipped with a state-of-the-art control unit for general use, should be built and extensively field tested to prove the high energy saving potential of this dryer concept.

6 Exploitation and Benefits

As a consequence of all the promising results for further developement and applications and in order to hold together the scientific know how cluster within the European Community all Partners are willing to form a new consortium. This consortium will/should be enlarged by additional partners (manufactures for components, heat pump assemblers and research related istitutions). It is the expressed goal of this group, to make an ambitious and attractive proposal within the Fifth Framework Programme for a new project of CO2 Heat Pumping Technologies.

Prototypes were developed, constructed and analized as test rigs from several partners for following applications:

- hot water heat pumps for residential applications [TUGRAZ.IFW]
- commercial heat pumps for water heating and heat recovery [SINTEF.RAC]
- heat pumps for space heating for retrofitting existing high-temperature systems [FKW]
- heat pumps for dehumidification and drying processes in residential and commercial applications [UESSEN.ATK].

Based on Copenhagen 1992 and the EU regulation of December 1994, CFCs and HCFCs have to be phased out. At present time many Fluor Carbons (FC`s, i.e. R 134a) and some Blends (i.e. R 407 C, R410A) are in the phase of market penetration, also some Flammables (i.e. R 290) and Ammonia are coming back. But none of these will meet the requirements of safety refrigerants:

- non toxic,
- non flammable,
- no ODP and
- no GWP.

Taking the old "natural" fluids, only water (R-717) and CO_2 (R-744) meet these requirements. The limitations of water are the freezing temperature of 0°C and the low volumetric capacity at temperatures below 100°C; the limitations of CO_2 have so far been the critical data, i.e. 31°C at 70 bar.

The trans-critical CO_2 cycle offers a completely new characteristic: While the Carnot cycle - most commonly utilized in vapor-compression systems - is suitable best for an unlimited heat source and heat sink, and the Lorenz and the Joule cycle for a limited heat source and heat sink with high temperature glides, the "Lorentzen-cycle" has its favorable application in the case of an unlimited heat source and a limited heat sink with high temperature glides. Ideal applications of this cycle are all processes, where the condenser inlet has a low temperature level - near the evaporating temperature - and the condenser outlet temperature required is high.

Due to the environmentally friendly behavior, which is guaranted by the refrigerant itself, safety aspects and energy efficiency will lead to wide spreaded applications with an unlimited heat source at constant temperature and a limited heat sink with a large temperature glide.

The advantages are:

Environmentally friendly behavior is guaranteed by the refrigerant itself. CO_2 is a safety refrigerant (not toxic and not flammable) and environmentally benign (no ODP, no GWP, no dangerous decomposition products).

Energy efficiency can be achieved by utilizing the unique characteristics of the new trans-critical cycle.

In the case of an unlimited heat source and a high temperature glide at the heat sink side, starting with a temperature similar to the heat source temperature, this cycle has no competitor if compared with cycles already in use.

Rather all results could fulfill the topics expected in the proposal to this poject and the fits between modelling and test analysises was extremely high. This is very promising in order to continue in CO2 technologies and to make further efforts for demonstration and dissemination of the resluts of this research project.

Only one not so successful topic occured. Compressors could be used for test rig installations from two manufactures (in Germany and Denmark). These comressors were prototypes and not produced within a mass manufacturing. An Italian manufacturer presented a new design at the CO2 work shop in Mainz, March 1999, which will offer new possibilities for the next steps in development and dissemination.

Design guide lines were developed for different applications by the responsible partners. These give a condensed overview about the essential topics, which have to be treated by further development and construction of CO2 heat pumping systems.

The individual risks identified can be compared with the risks generated by competing systems or similar systems.

With respect to an alternative heating system one could consider heating by means of natural gas. Statistical observations show that the individual risks connected with the use of natural gas is $1{,}9.10^{-6}$ per year. This is larger than the individual risk for type II heat pumps.

A comparison can also be made with R22 heat pumps. In general it is found that for the same application (temperatures) the explosive strength of 1 kg of CO_2 is some 3,5 times larger than that of 1 kg of R22. As a result of this an overpressure of some 40 mbar will be reached at a distance 33% larger for CO_2 than for R22 (for the same mass). This will be reduced by the fact that CO_2 results in smaller heat exchangers than R22, and therefore a smaller CO_2 charge. At any rate the probabilities will not be different for CO_2 or R22, only the impact distances maybe somewhat larger for CO_2.

It can be concluded that the risks related to the use of CO_2 in heat pumps are low and acceptable if the charge is limited such that concentrations in rooms after release of the charge are less than some 5%.