CO_2 THERMOSYPHONS AS HEAT SOURCE SYSTEM FOR HEAT PUMPS – 4 YEARS OF MARKET EXPERIENCE

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ABSTRACT

In Austria ground-coupled heat pumps are mainly used for heating only purpose in domestic applications. In principal two heat source systems are used: direct evaporation and secondary loop systems. These systems have been discussed to be harmful to the environment in the case of leakage and the later one needs an electrically driven circulation pump which reduces the system COP significantly.

A CO_2 probe based on the closed two-phase thermosyphon principle is a very promising alternative to conventional vertical systems. After a detailed experimental as well as theoretical investigation the first commercial system has been installed in 2001/02. Up to now about 100 systems are in operation: The efficiency of the heat pump system is higher for this 'advanced' system because of the natural circulation of the working fluid (CO_2) instead of a forced circulation in case of brine as the heat carrier.

The paper describes the principle design of the system, measured results as well as market experience collected so far with the CO_2 probes. Finally, a naturally circulating CO_2 collector, i.e. for horizontal installation, is introduced.

Key Words: ***self-circulation, ground-coupled, two-phase, probe, collector***

1 INTRODUCTION

After the second oil price shock in 1979 heat pumps installed in Austria were, like in other countries in Northern and Central Europe, heating-only systems, either ground water heat pumps for monovalent systems for new buildings equipped with floor heating systems or outside air heat pumps for bivalent systems, most commonly combined with existing oil-fired boilers, for retrofitting existing buildings with high-temperature heat distribution systems with radiators; the latter application dominated the market. The rapid drop of the oil price in 1985 in combination with the reduction of governmental subsidies eliminated the retrofit market, and for new buildings another heat source had to be found, and this heat source has been the ground.

In Austria, up to now direct-evaporation ground-coupled systems with horizontally installed ground coils (collectors) are dominating the heat pump market. Reasons are lower costs and higher efficiencies due to omitting the circulation pump and one heat transfer loss compared with secondary loop systems; the Seasonal Performance Factors (SPFs; i.e. the ratio of the thermal output to the electrical input during a heating season) of state-of-the-art systems are in the range of 4 to 5. In the case of limited ground area or existing houses, where the installation of the ground coils means a devastation of the garden, the alternative are vertical systems (probes). But in some regions licensing becomes difficult due to environmental concerns.

Austria has a continental climate with low temperatures in winter and relatively high temperatures in summer. The design temperature for heating systems is in the range of -10 to -16°C in the populated areas, where minimum morning temperatures of -20 to -25°C can be expected, the number of heating degree days is around 3500 Kd/a and the duration of the heating season is about 200 days or 4800 hours.

Why the ground is an excellent heat source for heat pumps can be seen from Fig. 1. The ground offers below the frosting depth – that varies from 0.6 to 1.2 m – a more or less constant temperature all year long. The typical temperature of the undisturbed ground is approximately 8 to 12°C.

In order to guarantee sustainability, i.e. natural recharging during summer time, limits for the heat extraction from the ground have to be met. The guideline (VDI 4640) describes such limits for probes and collectors. According to this guideline, the maximum extraction rate for a normal (wet) sediment is approximately 50 W/m_{probe}, thus a probe length (depth) of 16 m is required per kW-thermal output for a heat pump system achieving a SPF of 4.5. That means, a heat pump system for a building with a heating capacity of 8 kW at the design temperature requires a probe length of approximately 130 m, or two probes with each 65 m. (Remark: These numbers are based on heat extraction only, and a maximum operation time of 1800 h/a during the heating season.)

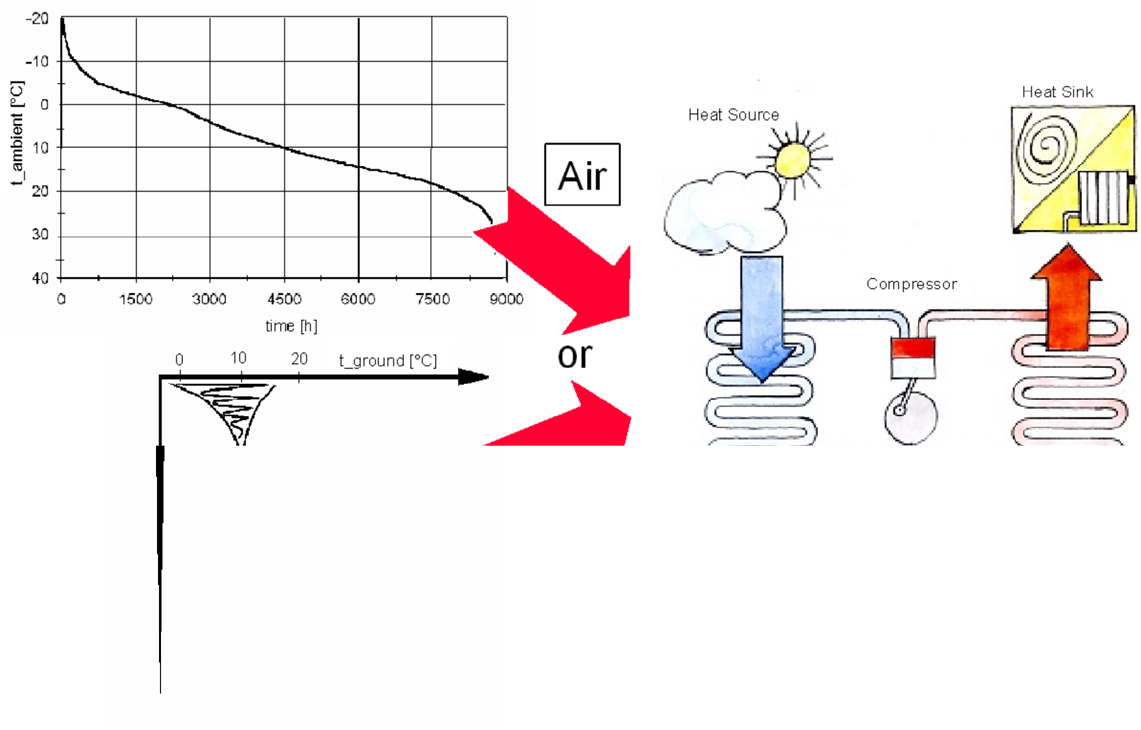

Fig. 1. Heat Sources - Adjusted temperature of the ambient air in Graz and typical ground temperature

The working principle of the proposed thermosyphon for probes – which is physically a closed two-phase thermosyphon – can be described as follows (compare Fig. 2): due to gravity the saturated liquid fluid flows along the tube wall to the 'heated' section of a pipe where it evaporates, thus the liquid film becomes thinner and thinner while the generated vapour rises to the top. In the 'cooled' section at the top the vapour condenses and the cycle starts again.

For the application discussed, the heat exchanger section buried in the ground corresponds to the 'heated' section and the probe head, i.e. the refrigerant evaporator of the heat pump, corresponds to the 'cooled' section of the thermosyphon.

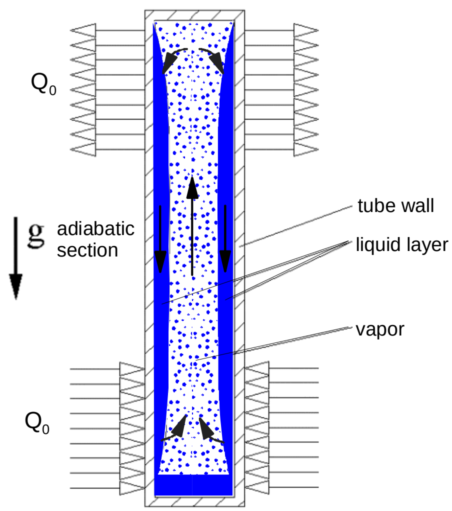

Fig. 2. Working principle of a closed two-phase thermosyphon (right)

During the development phase different working fluids in the thermosyphon have been tested, e.g. R22, R134a and R290 (propane). However, CO_2 (R744) turned out to be the favourite because the system works reliably, highly efficient, and last but not least CO_2 is harmless to the environment.

In such a CO_2 thermosyphon used as heat carrier system from the ground to the heat pump both the heat absorption and the heat rejection takes place at a sub-critical pressure, but close to the critical point (31°C/74 bar), because the temperature level during operation is about 0°C. At 0°C the saturation pressure of CO_2 is about 4 to 12 times higher compared to HFC refrigerants. For instance, at 0°C the saturation pressure is about 35 bar for CO_2, 8 bar for R410A, and 3 bar for R134a.

Owing to the low critical temperature, the vapour density of CO_2 is high: At 0°C it is approximately 7 times higher than those of R134a. The high vapour density results in the high volumetric refrigeration (cooling) capacity of CO_2. At 0°C it has a value of 22,500 kJ/m^3 for CO_2, and for R134a it is 2,900 kJ/m^3. The assumption that the low ratio of liquid to vapour density of CO_2 (it is about 10 at 0°C) may lead to a bad self-circulation characteristic is not correct and disproved by the experimental results (see below). Reasons for the good suitability of CO_2 in a thermosyphon are e.g. the high gradient of the saturation pressure (ca. 1 bar/K), the favourable pressure drop and heat transfer characteristics as well as the high refrigeration capacity which results in a very low mass flow rate in the thermosyphon.

Following chapters describe the layout of the proposed ground-coupled heat pump system, practical experience, and finally a horizontally installed CO_2 collector is discussed.

2 SYSTEM LAYOUT & TEST RESULTS

The proposed system is a refrigeration cascade consisting of several parallel thermosyphons in which CO_2 evaporates, and 'probe heads' which are the CO_2-condensers and refrigerant-evaporators of the heat pump (compare Fig. 3). This heat pump may supply a low-temperature hydronic heating system (Q_h). In the probe heads the heat extracted from the ground (Q_0) is transferred to the heat pump cycle, and they separate the CO_2 thermosyphons from the refrigerant cycle of the heat pump, thus pure CO_2 without any environmentally harmful substances circulates naturally in the ground heat exchanger; i.e. in case of leakage no risk of ground water contamination exists.

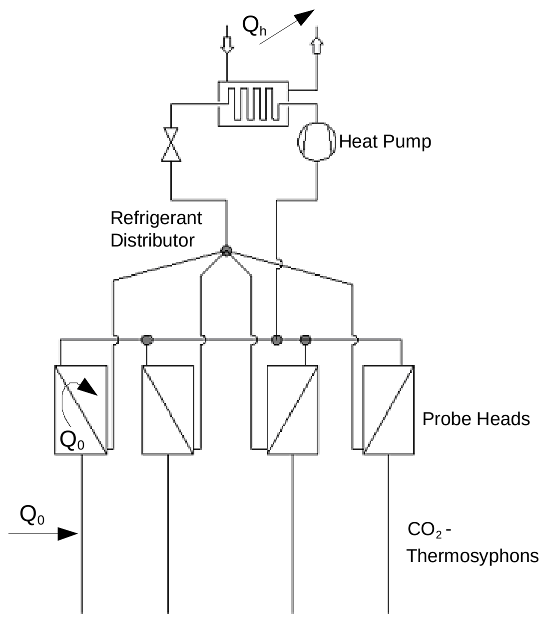

Fig. 3. System layout

The development of the proposed system – consisting of heat pump and thermosyphon – has started in the year 1997. Before the market introduction took place in 2001/02 prototypes have been investigated in detail by means of extensive measurements. The following paragraphs describe briefly some of the experimental results carried out with one of the prototypes, which is in operation since autumn 2000:

The heat pump supplies heat to a low-temperature hydronic heating system of an office building. The system is equipped with two 65 m bore holes each with 4 CO_2 thermosyphons, the heat pump uses R410A as the refrigerant, the heating capacity is about 9.5 kW, and a special control strategy allows a minimization of the super-heat at the evaporator outlet (typically lower than 3 K). The heat pump is located in the building while the probe head is located on the top of each of the earth probes.

Fig. 4 shows typical temperatures and capacities. The index 'evap' indicates evaporator and 'cond' condenser of the heat pump (R410A) cycle. As one can see, the time of operation was about 30 min followed by a stand-still of about 50 min.

The R410A condensation temperature was about 30°C and the evaporation temperature between -1.7 and -2.7°C. The heating (condenser) capacity was about 9.3 kW and the evaporator capacity of all 8 probe heads about 7.6 kW. These capacities correspond to a Coefficient of Performance (COP, i.e. the ratio of the condenser capacity to the power consumption of the compressor) of about 5.5 if losses to the ambient are neglected. The evaporator capacity and probe head capacity, respectively, corresponds to the overall extraction capacity of both bore holes; the extraction rate was about 58 $W/m_{borehole}$.

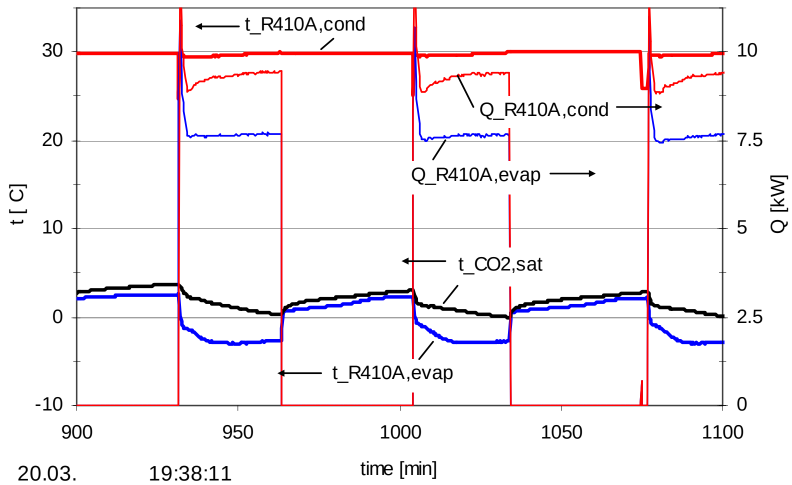

Fig. 4. Typical system temperatures and capacities

The temperature difference between the condensing CO_2 (t_CO2,sat) and the evaporating refrigerant (t_R410A,evap) is of high interest because it is a figure for the efficiency of the system (key word: additional temperature difference compared to a direct system): during this experiment it was about 3 K. This small temperature difference in the heat exchanger is only possible if the refrigerant super-heat at the evaporator outlet is minimized.

The analysis of the start-up behaviour has shown that almost no delay between the start-up of the heat pump and the response of the CO_2 cycle occurs even if the heat pump was not in operation for a long time, e.g. after the summer.

The saturation pressure along a thermosyphon increases due to gravity. Of course, a pressure increase means a disadvantage, but the CO_2 properties are very favourable because the effect in temperature increase is moderate. Simulations as well as measurements have shown that in a 65 m deep thermosyphon the increase in saturation temperature is less than 2 K. More information on this and further experimental data can be found in (Rieberer et al. 2004).

3 MARKET EXPERIENCE

Here follows some information about the number of installations and a description of some important design issues.

3.1 Examples of installed systems & Market Experience

As already mentioned, about 100 heat pumps equipped with CO_2 probes (each with several parallel thermosyphons) have been installed in Austria since 2001. The heat pumps are used for different purposes: heating of single and multi family buildings as well as for hot water production. As the required borehole depth depends mainly on the heat demand and the properties of the ground different lengths (depths) of probes have been realized. Fig. 5 shows the relevant numbers of installations and realized CO_2 probes (Remark: Many of the heat pump installations are equipped with more than one borehole, thus the number of installed probes is higher than the number of heat pump installations.)

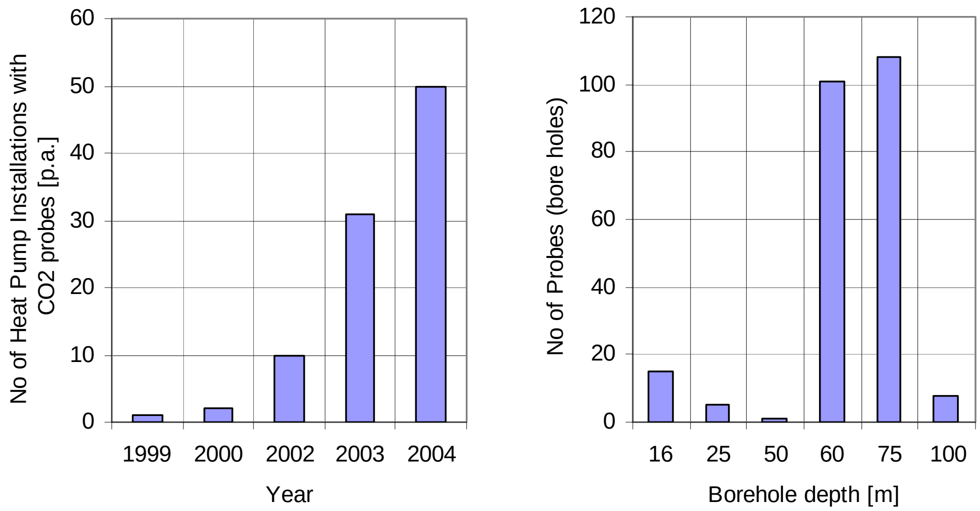

Fig. 5. Number of installations (left) and realized probe lengths (right)

Fig. 5 confirms the increasing interest in CO_2 probes. During the last years a progresses with respect to drilling and installation technology as well as probe design (especially of the probe head) have been obtained. This resulted in a high-quality as well as environmentally friendly product having approximately the same prize like a brine system for single-family buildings. Of course, in some matters room for optimization exists.

Due to the environmental benefit of CO_2 the authorities accepts the installation of CO_2 probes even in ground water protected areas. However, a detailed information policy is necessary to convince the people involved as it is a new technology.

3.2 Optimization

The reduction of the first cost was the key-issue after installing the first units. Following paragraphs summarize the most important facts.

a) Probe Material

Different materials have been investigated. A coated cupper tube turned out to be the best solution, because of the advantages with respect to standards, availability, abrasion, transportation to and construction at the site, as well as the unproblematic connection to the probe head. These features result in economic probes.

b) Geometry of the probe head

The ‘bottleneck’ of the system is the probe head which connects the CO_2 cycle with the heat pump cycle (CO_2 condenser / refrigerant evaporator). The natural circulation of the CO_2 demands a minimum pressure drop in this component, but an efficient heat transfer. Furthermore, the high working pressure on the CO_2 side which is typically between 30 and 55 bar requests a proper design.

Fig. 6 shows some design examples: While a ‘pot’ design demands rather large wall thicknesses, the serpentine design may cause problems with respect to liquid return to the probe. The spiral type is very efficient, but demands a rather large installation space. In other words, these types are not the optimum solution because of problems due to the rather high pressure, space requirement, first cost and/or construction. The newly developed vertical type combines the advantages of the previous ones but without the disadvantages of them.

Fig. 6. Different probe head geometries (pot, serpentine, spiral, and vertical type)

c) Number of probes in one borehole

An interesting question is, how many single probes (thermosyphons) should be installed in one borehole. Of course, one has to meet the maximum heat extraction out of one borehole in order to guarantee sustainability (see above).

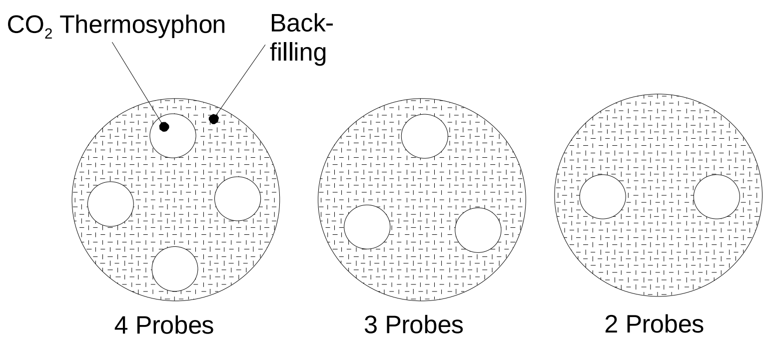

Fig. 7. Number of single CO_2 probes (thermoysphons) in one borehole

By means of FEM (finite element) simulations it was tried to find an answer for the optimum number of thermosyphons in one borehole. In (Rieberer et al. 2004) an example for the calculated temperature distribution in the backfilling material (bentonite) with two and three thermosyphons can be found.

The temperature drop in the backfilling material decreases as the number of parallel thermosyphons and heat exchanger area, respectively, increases. Additionally, the risk of a destruction of the liquid film running downwards by the vapour flowing upwards is reduced (compare Faghri 1995).

However, the gain diminishes as the number of parallel thermosyphons is higher than 4. In other words, the installation of more thermosyphons can not be justified because the increase of the SPF or the reduction of the running costs, respectively, is negligible while the installation of more thermosyphons results directly in an increased installation cost.

d) Installation of the probes

The photographs shown in Fig. 8 document the progress in installation technique: While at the beginning it was a very time-intensive job to install the (up to 100 m long) probes, the installation procedure is already standardized resulting in a very fast and cheap installation of the tubes.

Fig. 8. Installation of the probes (left: one of the first installations; right: standardized)

e) Probe length

Up to now the standard lengths (depths) of the probes are 60 and 75 m (compare Fig. 5). In order to reduce the first cost, a probe length of up to 100 m is under investigation at the moment. This length offers the possibility, that for many buildings one borehole is sufficient. First heat pumps with 100 m probes are already in operation.

f) Inclined boreholes

As the heat extraction rate per meter borehole (depth) is limited it is necessary to realize more boreholes if the heat demand can not be covered by one. In (VDI 4640) one can find a minimum distance for the boreholes (s_min = 5 to 6 m). This causes a rather inconvenient distance of the probe heads which have to be connected with the heat pump. The distance between the probe heads could be reduced, if the boreholes are not vertical but inclined as indicated in Fig. 9.

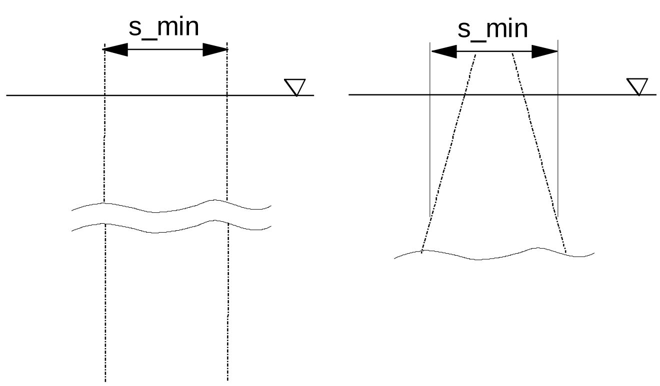

Fig. 9. Minimum distance between boreholes

The question arises whether the natural circulation of the CO_2 is negatively influenced by this arrangement. First tests have shown that the CO_2 circulation is hardly effected up to a relatively large angle, thus the next step is to install a prototype based on this idea.

g) CO_2 charge and charging procedure

It is evident that a thermosyphon is sensitive with respect to under- and over-charging. Simulations have shown that a charge 7% lower than the optimum value results in a reduction of the evaporation temperature of about 1.7 K. On the other side, over-charging does not influence the performance very much: for an overcharge of 20% the calculated temperature reduction is lower than 0.3 K.

For the experimental determination of the optimum (minimum) charge some thermosyphons have been equipped with temperature sensors at the bottom in order to check the ‘activity’ at the deepest point; activity is indicated by a ‘significant’ drop of the tube wall temperature at a certain CO_2 charge.

Up to now sufficient data for the optimum CO_2 charge depending on the probe head geometry and the probe length have been collected. At the moment a pre-filling of CO_2 bottles with the optimum mass of CO_2 is under investigation, because this would allow a very convenient charging procedure.

4 OUTLOOK – CO_2 COLLECTOR

Initiated by the great success of the CO_2 probe, and the knowledge of both the high drilling cost and the large market share of horizontally installed systems, a CO_2 collector which is also based on the thermosyphon principle is investigated theoretically and experimentally at the Institute of Thermal Engineering.

The system consists of the CO_2 collector connected to the heat pump by means of the so-called ‘collector head’ (compare Fig. 10): CO_2 circulates naturally in the collector driven by the density difference between the liquid CO_2 entering the collector tube and the (partly) evaporated CO_2 at the outlet from the collector.

As it is indicated in the figure, the test rig is not buried in the ground but heated by the ambient air in the laboratory. However, the main operating characteristics can be transferred to a ground coupled system, because experience confirms that tests at ambient air (20°C) correspond approximately to ‘real’ conditions (soil, 7°C); the low overall heat transfer coefficient from the air to the fluid flowing in the collector is compensated by the increased temperature difference.

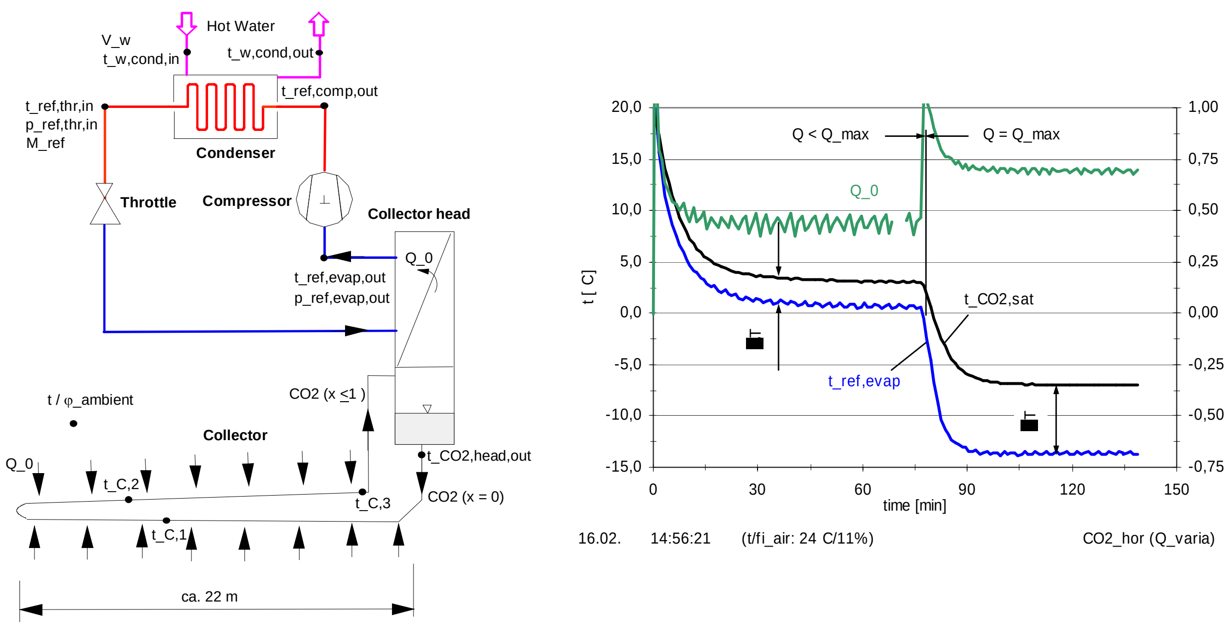

Fig. 10. CO_2 collector – layout and initial experimental result

Several sensors have been installed in order to determine the operational characteristic of the system, e.g. 3 thermocouples on the tube wall of the 45 m long collector are used to observe the ‘CO_2 activity’.

The initial experimental results confirm the suitability of the proposed system: the natural circulation starts immediately after the start-up of the heat pump and the required temperature difference (ΔT) between the condensing CO_2 and the evaporating refrigerant in the collector head is acceptable if taking into consideration that this is the very first design. However, the initial test runs have shown that the system is very sensitive with respect to undercharging and to the capacity transferred in the collector head (Q_0).

An extensive experimental as well as theoretical investigation is planned in order to study in detail the influence of the CO_2 charge and the capacity on the performance, i.e. the temperature difference between CO_2 and evaporating refrigerant. For the analysis of the required temperature difference between ground and evaporating CO_2 in a 'real' collector, the installation of a first prototype system is planned.

5 CONCLUSIONS

Since 1999 several prototype systems with CO_2 probes have been tested and about 100 systems have been sold. During the last years the investigations have been focused on the system optimization in order to offer an economically competitive product on the market. These activities resulted in comparable prizes for CO_2 and brine based probes.

A CO_2 collector may open a large market as the installation is much cheaper compared to probes. Initial tests with a test rig have proven the suitability of the naturally circulating system. The next step is the detailed investigation of the operational characteristic of this system, mainly the effect of varying CO_2 charge and capacity.

If one compares brine systems with naturally circulating CO_2 probes and collectors following advantages can be summarized:

- The self-circulation (instead of forced circulation by a pump) leads to a reduction of the electricity consumption,
- potential defects of the circulation pump are eliminated,
- CO_2 offers better heat transfer characteristics, and
- it is absolutely harmless to the ground.

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