SOLAR COOLING AND REFRIGERATION WITH HIGH TEMPERATURE LIFTS – THERMODYNAMIC BACKGROUND AND TECHNICAL SOLUTION

Hans-Martin Henning[1], Andreas Häberle[2], Marco Guerra[3], Mario Motta[4]
1 Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany
2 PSE GmbH, Freiburg, Germany
3 ROBUR SpA, Verdellino/Zingonia (Bg), Italy
4 Dip. Energetica, Politecnico di Milano, Milano, Italy

ABSTRACT
The need for air-conditioning in buildings and for industrial process cooling - e.g., in food industry - is growing rapidly all over the world. A new promising approach to meet this increasing demand in an environmentally sound way is the use of solar energy in combination with heat driven cold production. Many technical solutions are possible to use solar heat for air-conditioning. Key issues for system design and selection of components are:

- The selection of the room air-conditioning distribution systems: e.g., radiative ceilings and other ”high temperature” systems need only chilled water temperatures in the range of 15-18°C while chilled water networks supplying fan-coil systems require temperatures at 7-10°C.
- The heat rejection technology used: a wet cooling tower allows for lower heat rejection temperatures than dry air-cooling.
- The presence and size of a storage to overcome mismatches between solar gains and cooling loads. A very attractive solution in terms of energy density is an ice storage; however this storage requires cold production temperatures below 0°C.

The system selection is mainly based on climate and load conditions analysis and on the energy (electricity, back-up fuel) and water costs and availability. In this paper a basic thermodynamic analysis is presented which gives insight into the interaction between the selection of the proper technical solution and the climate and load conditions. In the second part of the paper a special focus is given on a newly designed system which can be applied under extreme climatic conditions, i.e., hot and humid climates.

INTRODUCTION

Air-conditioning represents a growing market in building services world-wide in both commercial and residential sectors. Main reasons for the increasing energy demand for summer air-conditioning are the increased thermal loads, increased living standards and occupant comfort demands as well as building architectural characteristics and trends, like an increasing ratio of transparent to opaque surfaces in the building envelope to even the popular glass buildings. Air-conditioning includes both temperature and humidity control of indoor air.

Particularly for large systems in the range of about 35 kW and above, different heat driven cooling technologies are available on the market, which can be used in combination with solar thermal collectors. The main obstacles for large scale application, beside the high investment costs, are the lack of knowledge and practical experience on: design, control and operation of these systems. For small scale applications, up to few years ago, no appropriate technology was available on the market. However, recently several companies started development of water chillers in the power range below 35 kW down to 5 kW and first commercial systems are now available. But still the further development of small capacity cooling and air-conditioning systems remains of high interest.

CLASSIFICATION OF SOLAR COOLING SYSTEMS

Conversion of solar radiation in cooling

From a thermodynamic point of view there are many processes conceivable for the transformation of solar radiation in cooling. An overview is given in Figure 1.

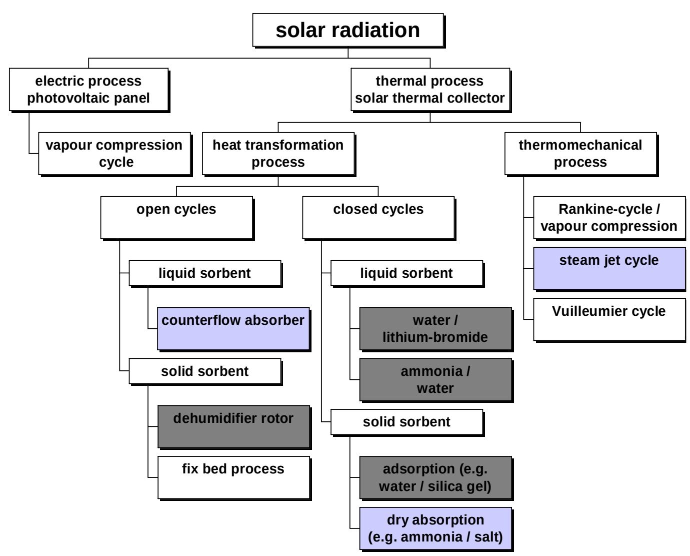

Figure 1 - Overview on physical ways to convert solar radiation into cooling or air-conditioning. Processes marked in dark grey: market available technologies which are used for solar assisted air-conditioning. Processes marked in light grey: technologies in status of pilot projects or system testing.

Although the conversion of electricity by photovoltaics and the subsequent use of this electricity in a classical motor driven vapour compression chiller is a technically feasible concept, it is not further considered here. Reason is, that in industrialised countries, which have a well-developed electricity grid, the maximum use of photovoltaics is achieved by feeding the produced electricity into the public grid. In economic terms, from the user point of view, this is even more valid if the price payed for electricity generated by solar energy is higher than electricity's cost from conventional sources (e.g., feed-in-laws in Germany, Spain and Italy).

Among the thermally driven technologies, which use a solar thermal collector to provide heat to drive a cooling process, the technologies based on heat transformation are the best developed therefore only these systems are considered further.

From a system point of view a classification can be made in systems which produce chilled water and system which directly produce conditioned air, i.e., ventilation systems that provide fresh air with low temperature and humidity (desiccant system).

Open cycles – desiccant cooling systems

This article covers mainly systems employing water chillers. However, it has also to be mentioned that open cooling cycles employing desiccant materials provide another option to use solar thermal energy for cooling applications; therefore a short description of these systems is given further.

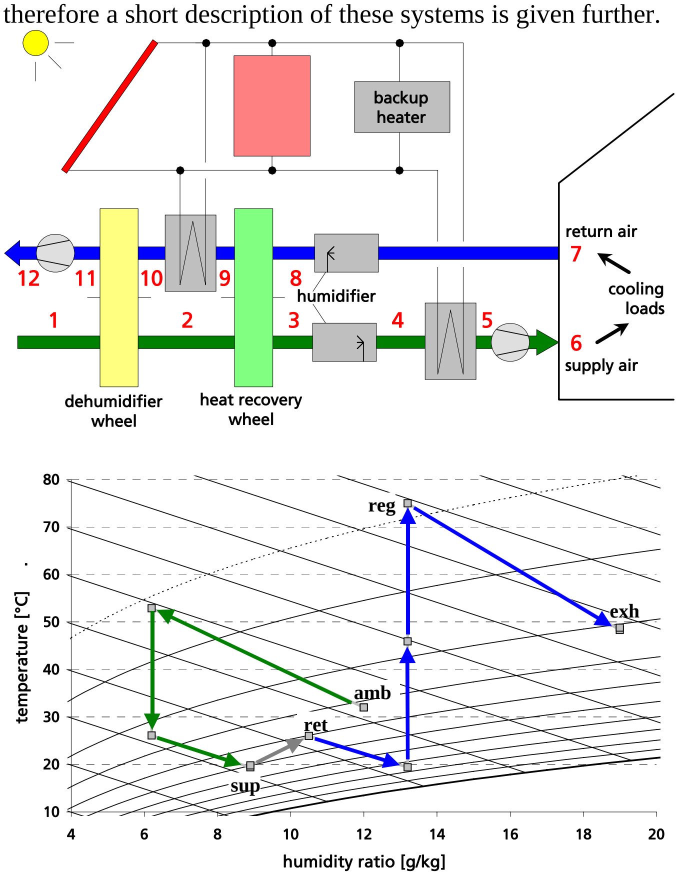

Figure 2 - Standard desiccant cooling cycle using a dehumidifier wheel with solar thermal energy as driving heat input (top) and the change of the air states during the process in the T-x-diagram of humid air (bottom)

While thermally driven chillers produce chilled water, which can be supplied to any type of air-conditioning equipment, open cooling cycles produce directly conditioned air. Any type of thermally driven open cooling cycle is based on a combination of evaporative cooling with air dehumidification by a desiccant, i.e., a hygroscopic material. Again, either liquid or solid materials can be employed for this purpose. The standard cycle which is mostly applied today uses solid sorbent materials (i.e., silica gel or lithium-chloride) fixed on a rotating desiccant wheel. A simplified scheme of a solar desiccant system and the thermodynamic path of a standard process are shown in Figure 2.

Systems employing liquid sorption materials which have several advantages like higher air dehumidification at the same driving temperature and the possibility of high energy storage by means of concentrated hygroscopic solutions are close to market introduction. Desiccant cooling systems are an interesting option and ongoing developments on advanced cycles promise to increase their applicability in combination with solar thermal energy. More details about the technical background of these technologies –can be found in [1].

Chilled water systems

A basic figure to describe the quality of the conversion of heat into cold is the thermal Coefficient of Performance, COP, defined as the useful cold, Q_{cold}, per unit of invested driving heat, Q_{heat}:

$$COP = \frac{Q_{cold}}{Q_{heat}} \qquad (1)$$

The first and second law of thermodynamics applied to the basic process of a thermally driven chiller according to a scheme shown in Figure 3, lead to an expression for the maximum possible Coefficient of Performance, COPideal, in which the COP is only dependent of the three temperature levels:

$$COP_{ideal} = \frac{T_C}{T_H} \cdot \frac{T_H - T_M}{T_M - T_C} \qquad (2)$$

where T_C is the temperature of the low temperature heat source (useful cooling), T_H is the temperature of the driving heat source and T_M is the intermediate temperature level at which the heat is rejected to a heat sink (in general environmental air using either a wet cooling tower or dry air cooling).

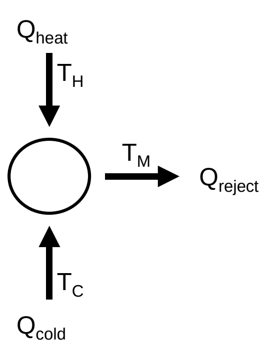

Figure 3 - Basic thermodynamic scheme of a heat driven heat pump or chiller, respectively.

The COP calculated according to equation (2) gives the upper thermodynamic limit which can never be achieved in practice. Real COP-values of thermally driven chillers available on the market are shown in Figure 4 together with the COP_{ideal} calculated according to equation (2). The figure shows the COP characteristic of the most common thermally driven water chillers, namely a single-effect LiBr-water absorption chiller, a double-effect LiBr-water absorption chiller and an adsorption chiller which uses silica gel as sorption material. The figure indicates that for typical single-effect absorption systems driving temperatures in the range of 80-95°C are necessary and COP-values in the range of 0.7 are reached. For double-effect systems driving temperatures in the range of 140-150°C are necessary; therefore higher COP-values in the range of 1.2 are attained. Adsorption systems can be operated with somewhat lower temperatures than single-effect absorption machines (temperatures in the range of 60-80°C), but they achieve somewhat lower COP-values in the range of 0.6.

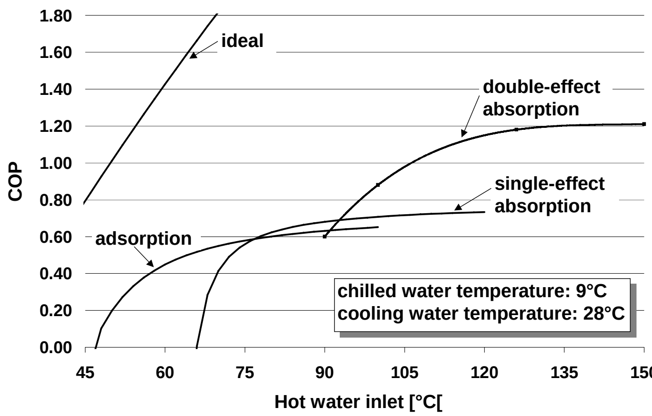

Figure 4 - COP-curves of sorption chillers and the upper thermodynamic limit (ideal) according to Eq. (2).

THERMODYNAMIC ANALYSIS OF SOLAR COOLING SYSTEMS (CLOSED CYCLES)

The fraction between real COP and maximum, ideal COP at the same conditions is called Carnot Efficiency Factor,

$$\xi_{Carnot} = \frac{COP_{real}}{COP_{ideal}} \qquad (3)$$

This factor lies in the range of 0.3 to 0.4 for common market available systems. The ξ_{Carnot} can be increased by any measure which reduces the impact o thermodynamic irreversibility, such as improved heat recovery in the internal cycle, optimized heat exchanger etc..

With good approximation the COP_{ideal} is a function of the difference between the heat rejection temperature, T_M, and the temperature of the low temperature heat source, T_C. This temperature difference ΔT is called the required temperature lift:

$$\Delta T = \left(T_M - T_C\right) \qquad (4)$$

In Figure 5 the required temperature of the heat source – the solar collector in case of solar cooling – is plotted as function of the required temperature lift; the curves are based on the COP of an ideal thermally driven chiller according to equation (2), multiplied with the Carnot Efficiency Factor ξ_{Carnot}. Although this characteristic of an ideal cycle is not completely identical to that of real systems it can be well used to demonstrate the influence of the temperature lift on the required driving temperature and thus with the selection of the appropriate solar collector technology at different load conditions. Four different lines are shown which refer to different COP-values, namely 0.7 and 1.1, and different Carnot Efficiency Factors, namely 0.3 and 0.4.

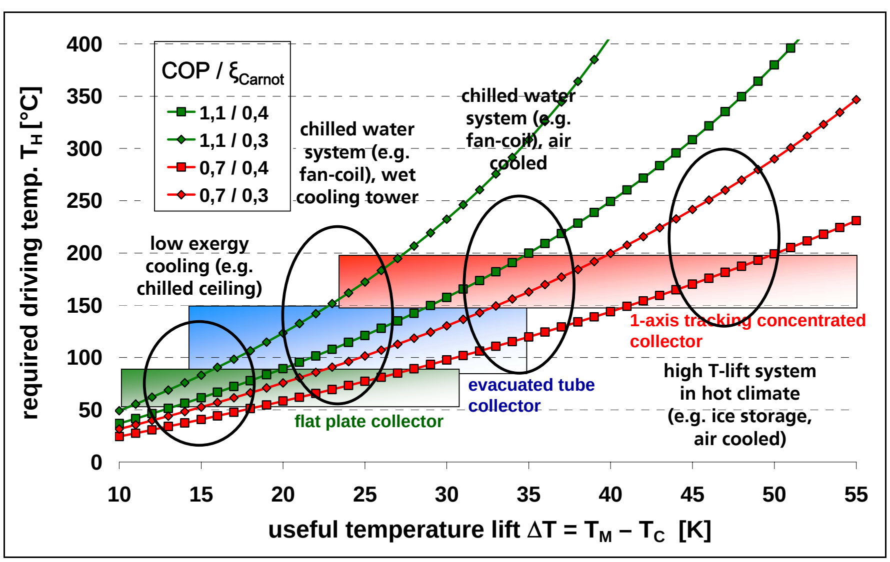

Figure 5 - Required heat source temperature as function of the required temperature lift between required temperature of cold production (low temperature heat source) and temperature for heat rejection. Curves refer to different COP/ξ_{Carnot} combinations. Typical operation temperature ranges of different solar collector technologies are marked by coloured areas. The ellipses indicate different system designs.

System design based on thermodynamic analysis

A first important step in the design process of solar cooling systems is to define the required temperature lift. Different systems and applications can be compared and some important examples are described below:

Figure 6 – Low temperature lift system: Low exergy cooling system using chilled ceilings, a low temperature driven single effect absorption chiller (LiBr-water chiller from company Phönix Sonnenwärme) and a flat plate collector

In case of a low exergy cooling system, i.e., a system which can be operated with a low temperature difference between room temperature and temperature of the cold water such as a chilled ceiling, a *low temperature lift* in the range of 15 K will be sufficient, at least in moderate climates. Such system can be operated using flat plate collectors. An example is shown in Figure 6.

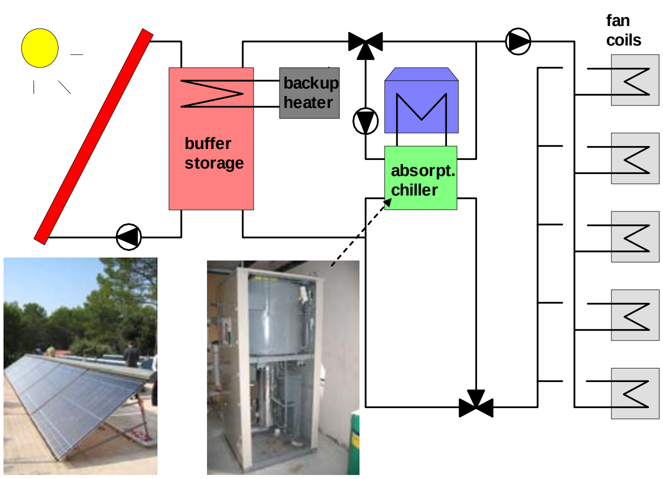

Figure 7 – Medium temperature lift system: fan coil system with single effect absorption chiller (LiBr-water chiller from company Yazaki) and an evacuated tube collector field to provide driving heat

A common fan-coil system, in which dehumidification is realized by cooling the air below the dew point needs chilled water in the range of 6-8°C. With a temperature for heat rejection in the range of 35°C a temperature lift of about 25-30 K is necessary. For this example of a *medium temperature lift system* very high efficient flat plate collectors or evacuated tube collectors are necessary in case of single-effect chillers (lower COP-value); see Figure 7. For double-effect chillers (high COP-value) possibly high efficiency evacuated tube collectors can be employed but in most cases collector systems with optical concentration, which are tracking the sun will be necessary (Figure 8).

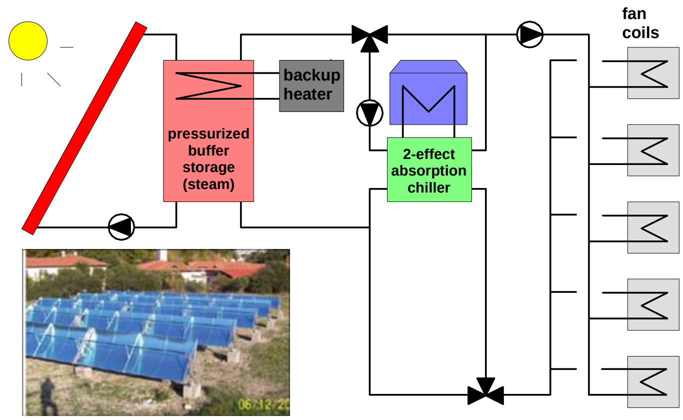

Figure 8 - Medium temperature lift system: fan coil system with double effect absorption chiller and single-axis tracking parabolic trough collector to provide driving heat

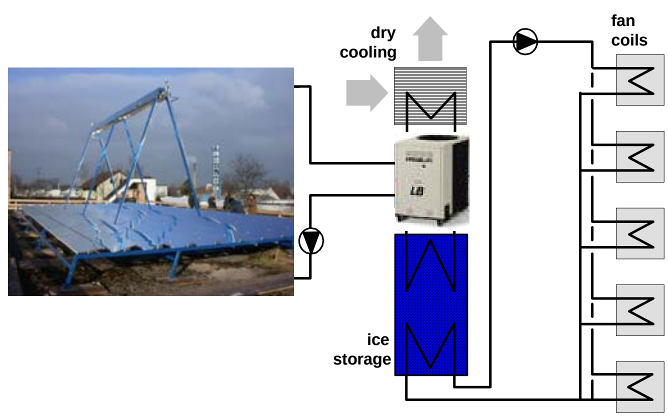

Figure 9 – High temperature lift system: Fresnel type single-axis tracking solar collector provides high temperature to run a single-effect high temperature lift absorption chiller (ammonia-water chiller from Robur) with ice storage and fan-coil system

Under conditions of high ambient air temperatures (e.g. higher than 35°C) in which no wet cooling tower can be employed (e.g. due to high wet bulb temperatures or no availability of water) a *high temperature lift* will be necessary. This is even more valid if a low temperature on the cold side is needed e.g. in case of ice production or using an ice storage to overcome mismatches between cooling load and solar gains. Under those conditions only a single-effect machine (low COP-value) can be used if driving temperatures up to approx. 200°C are available. A collector system with optical concentration will be necessary in such case. These conditions correspond very much to the needs in hot, arid regions in which fresh water is costly or a scarce commodity; an example is shown in Figure 9.

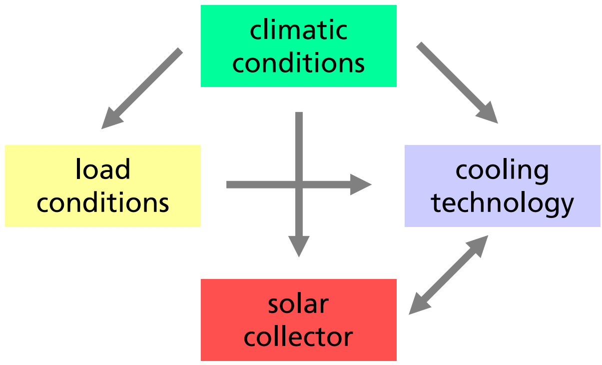

Figure 10 – Interdependencies between climatic conditions and load conditions and the employed technology for cooling and solar collector

Which system is selected for a given application depends on many boundary conditions; the interdependencies between the key categories of conditions and technologies are shown in Figure 10. The following interdependencies exist:

- It is obvious that the load directly depends mainly on the climatic conditions. All the meteorological parameters – temperature of the environmental air, humidity ratio of the environmental air and solar radiation – have a direct influence on the cooling (and heating) loads of a building.
- Both, temperature of the environmental air and solar radiation available have an influence on the solar collector performance. Tracked collector systems employing optical concentration with concentration factors above approx. 2 require a climate with a high fraction of direct solar radiation, since diffuse radiation cannot be concentrated by geometric optics.
- Climatic conditions, i.e., temperature and in particular the humidity ratio of the environmental air also influence the cooling technology since in climates with high humidity a wet cooling tower is not applicable or does not provide a big advantage compared to dry re-cooling. Thus higher re-cooling temperatures are predominant and an appropriate chiller has to be employed.
- The load conditions also influence the cooling technology. In buildings with a high need for air refreshment an air handling unit using an open desiccant cycle may be the appropriate technical solution, while in buildings with low need for ventilation air a chilled water system will be favourable.
- Finally a close interdependence between the distribution system, the employed cooling technology and the solar collector exists due to the the necessary temperature lifts and driving temperature requirements of the cooling technology, as it is shown in Figure 5 and the subsequent examples in Figure 6 to Figure 9.

Figure 4 and Figure 5 also show that in principle two tracks are possible in order to improve the efficiency of solar cooling systems. On the one hand using a high efficient solar collector allows higher driving temperatures and thus an increased COP (see Figure 4). On the other hand an increase in the Carnot Efficiency Factor allows operation of a thermally driven chiller at lower operation temperatures and thus at increased collector efficiency (see Figure 5). Both tracks are subject of ongoing R&D activities.

A NEW HIGH TEMPERATURE LIFT SYSTEM

In this section we describe a newly designed system which can be applied under extreme climatic conditions, i.e., hot and humid climates, and can be used for both comfort air-conditioning and refrigeration.

Basic system description

The key components of this system are a water-ammonia heat pump and a single-axis tracking line-focusing solar collector based on the Fresnel concentrator approach. Recently the German company PSE GmbH (Freiburg, Germany) and the Italian producer of ammonia-water absorption heat pumps Robur S.p.a. (Zingonia-BG, Italy) started a co-operation on the development of this system. Politecnico di Milano and Fraunhofer ISE are involved as R&D service providers for support of system design, simulation, monitoring and evaluation.

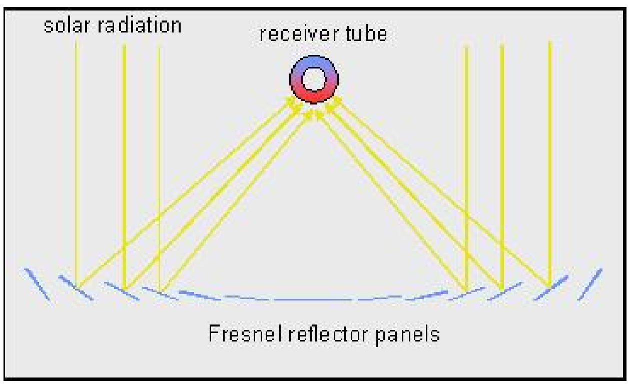

Figure 11 – Principle of the fresnel reflector (without secondary concentrator)

Figure 12 – Photograph of the first prototype Fresnel collector of PSE

The solar collector is a newly developed single-axis tracking concentrating collector. The specific feature of this new collector is that a number of almost flat mirrors are individually tracked on a stationary receiver. The absorber pipe is mounted on top of the mirrors. A scheme of this so called linear Fresnel collector is shown in Figure 11 and a photograph in Figure 12.

The second main component is the ammonia water chiller which allows a high temperature lift, i.e., a low temperature on the useful cooling side and a high temperature for heat rejection. Robur produces this technology since many years for application as gas driven heat pumps. In order to allow the combination with a solar collector system as heat source, the flue gas heat exchanger to operate the generator in the ammonia/water heat pump cycle had to be replaced by a heat exchanger heated by a liquid such as a synthetic oil or pressurised water. A photograph of the chiller is shown in Figure 13.

Figure 13 – Photograph of Robur ammonia-water heat pump; the machine is directly air-cooled and does not need an extra cooling tower

System characteristics

The new system has the following main advantages:

- Due to the high temperature lift of the absorption chiller it is possible to employ a dry air heat rejection system driving the chiller with temperatures bearable by a conventional concentrating collector. Thus no water is needed and correspondingly the maintenance is lower than for systems with wet cooling towers. This advantage is particularly important in regions where water is rare or costly.
- Due to the high temperature lift also very low temperatures on the cold side can be achieved. This allows production of ice e.g., for conservation applications or ice storage. An ice storage has a very high energy density and thus is an efficient solution to overcome mismatches between cooling loads and solar gains.

As shown in Fig.5, such a system requires high generation temperatures (in comparison to systems which achieve lower temperature lifts) and therefore high efficient concentrating solar collectors have to be employed. Although high temperatures are used only the COP of a single-effect can be achieved as can be seen from Figure 5; again the reason is the high temperature lift.

Pilot installations for food conservation

In the near future an international project will begin, in which the new concept will be developed for solar refrigeration for the food and agro industry in southern European countries. The project entitled “MEDISCO - MEDitarranean food and agro Industry applications of Solar COoling technologies” will be funded by the European Union (DG Transport & Energy) and is co-ordinated by Politecnico di Milano, Department of Energy studies.

The main goals of the project are:

- Installation, commissioning and optimisation of two solar driven cooling systems in North African countries (e.g. Tunisian winery).
- Development of guidelines for solar cooling systems in southern Mediterranean countries, in order to facilitate solar cooling technology diffusion and market growth.

SUMMARY

A thermodynamic analysis of solar cooling indicates that the temperature lift, i.e., the difference between heat rejection temperature and temperature on the cold side, is a crucial parameter for the design of the entire system. The lower the temperature lift, the lower may be the driving temperature or the higher is the possible efficiency (COP) for a given temperature. The analysis showed that in cases of required high temperature lift a high efficient solar collector system is needed such as a concentrating solar collector.

Two pilot systems using a concentrating solar collector system will be designed and installed in North African countries in the framework of a project funded by the European Union. The systems will produce cooling at low temperatures (ice production for food conservation) with dry heat rejection. First experimental results are expected for summer 2007.

NOMENCLATURE

COP	Coefficient of Performance [-]
COP_{real}	real COP of a machine [-]
COP_{ideal}	Reversible COP of ideal process [-]
Q_{cold}	Energy on cold side [MJ]
Q_{heat}	Driving energy [MJ]
T_C	Temperature on cold side [K]
T_M	Temperature on medium side [K]
T_H	Temperature on hot side [K]
ΔT	temperature lift [K]
ξ_{Carnot}	Carnot efficiency factor [-]

LITERATURE

[1] Henning, H-M. (Ed.), Solar-Assisted Air-Conditioning in Buildings – A Handbook for Planners, Springer Wien/NewYork; ISBN 3-211-00647-8