IMPROVMENT OF SOLAR COOLING PLANT PERFORMANCE BASED ON SIMULATION AND EXPERIMENTAL ACTIVITIES

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Synopsis

Solar refrigeration for dry hot climates has been achieved by developing a novel concept of high temperature lift solar cooling system. A pilot plant based on this concept was designed and installed for a Tunisian beverage factory in spring 2008. The development of the system concept, the detailed design and the components sizing have been implemented through simulations of the system behaviour using the TRNSYS's simulation platform. For this purpose mathematical models of the concentrating collector and the absorption chiller were developed and implemented. Results obtained from the monitoring activities of the system's performance were utilized for the TRNSYS models validation.. Therefore the validated models were used for further simulation campaign aiming to define the optimum operating points of the whole system and trace a path towards it's the plant performance improvement.

1. Introduction

Most of the solar cooling systems installed worldwide (about 300), are for air-conditioning applications, few systems are designed for industrial refrigeration. Moreover only few units were planned for the application in dry and hot regions. In order to investigate the technical feasibility of solar refrigeration in these regions A novel solar refrigeration system was designed, implemented and commissioned in Tunisia in 2008, a detailed monitoring system was installed and the monitored results were analyzed in accordance with the unified monitoring proposed in Task 38 SHC of the International Energy Agency (IEA). The work presented here explains the concept development, simulation models creation , validation and optimization of a novel solar cooling system installed in Tunisia for an agro-food industrial application within the framework of the EC co-funded project MEDISCO.

2. System Concept

The system concept presented has to answer to peculiar boundary conditions compared to common solar cooling applications. The plant serves as industrial refrigerator for a beverage factory in Grombalia (Tunisia); the system is requested to supply low temperature refrigeration (down to -8°C) while the ambient temperature reaches often 40°C during the hot season. Moreover, such system concept is intended for regions which faces water scarcity, suggesting to avoid the use of water based heat rejection technology and to select air cooled chiller. Considering the high temperature difference between the ambient and the chiller water temperatures (i.e., about 50 K), the plant can be classified as a high temperature lift system. While the low chilled water temperature required could be supplied by a single-effect water-ammonia chiller, the thermodynamic analysis of the system revealed that: only a single stage system can be employed for such applications and medium temperature collectors are required to deliver heat at the required temperature level to the chiller's generator as explained in details in [1] [2]. The system concept scheme is presented in Figure.1.

2.1 System Design through Simulation: models development of the main components

In order to size the plant components and carry out the system's detailed design, the starting point has been the analysis of the yearly refrigeration loads of the factory. Further several system configurations were analysed through simulations carrying out a parametric study on: energy storages size, backup systems, size and orientation of the collector. The numerous annual simulations resulted in a system design consisting of:

- Solar collector: Linear Fresnel collector oriented North-South, 120 m^2 gross area, 88 m^2 mirrors area.
- Chiller: 13 kW, single stage water ammonia absorption chiller cooled by air.
- Storages: 3 m^3 water-glycol cold storage to store the cold production of the chiller to be used when required by the load; no hot storage.

In order to be able to carry out the aforementioned simulation study, it has been necessary to develop and implement mathematical models of the main system components: are the Linear Fresnel solar collector and the absorption chiller. The Fresnel collector [3] is made of a primary linear Fresnel reflector, a secondary parabolic reflector and a vacuum absorber tube, Figure 3. The primary reflector is composed of several reflecting strips, which concentrate direct beam radiation on the secondary reflector. Mirror strips orientation can be varied according to radiation incident angle in order to maintain a fixed focus line. The single stage water ammonia thermally driven absorption chiller has been characterized in a static model based on a simple input – output relation table, compiled for a large combination of different inputs based on monitoring data acquired from previous installations. Detailed description of the collector and chiller TRNSYS models can be found in [4].

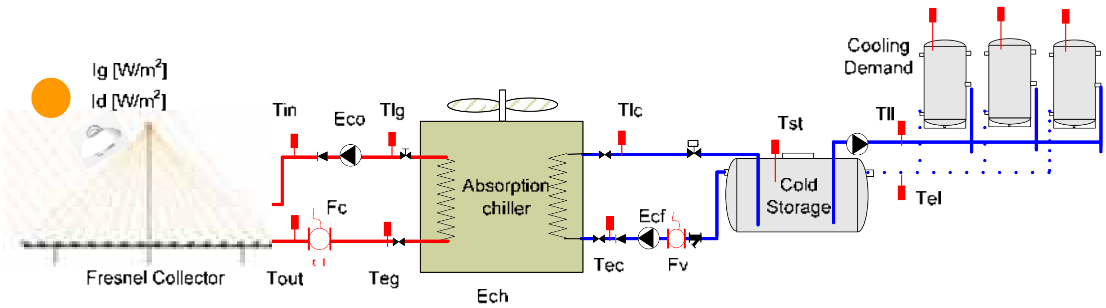

Figure 1 General system scheme showing monitored parameters.

2.2 Models validation

The system designed as explained in the previous section, has been installed in XXXX 2008. The prolonged experimental activities carried out on the solar cooling system resulted in sufficient spectrum of data that have been used to calibrate and validate the TRNSYS simulation models.

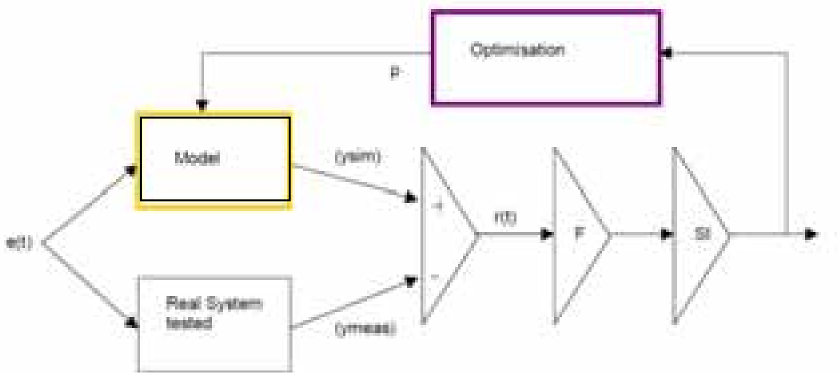

Figure 2 The dynamic fitting procedure. [5]

The validation procedure presented in Figure 2 derived from the “Parameter identification manual for TRNSYS models [5]” is has been applied as follows:

- The input e(t) in the Fresnel collector testing corresponds to the solar radiation, input temperature and flow rate. These inputs were measured in the real system operation.

- The same measured inputs are used as input signals applied to the TRNSYS model. Measured data for input solar radiation, temperatures and flows are read from a data file created by the measurement program.
- The measured output (ymeas) is compared to the simulated output (ysim), which is dependent on the parameters set p. The measured output, output temperature of the collector, is read directly from the same data file as the input data. The simulated values come directly from the simulation models themselves.
- The deviation (r(t)) is first filtered (F) to remove "noise" in the data, then squared and integrated (SI). The resulting signal gives a measure of the goodness of fit.
- An optimisation procedure –carried out through GenOPT- is used to derive the best parameter set p – i.e., to minimize r(t) and hence the difference between the simulated and measured output temperatures.

2.2.1 Linear Fresnel collector model validation

The efficiency curve for a solar collector, which determines the collector's performance at different radiation and temperature levels, given a set of boundary conditions. For a single axis-tracking collector, as the one analysed, the efficiency curve equation and parameters can be expressed as follows:

$$\eta = \eta_0 * IAM - a_1 * \frac{\Delta T}{G_{bn}} - a_2 * \frac{(\Delta T)^2}{G_{bn}}$$

Where, for the collector technology used in the installation mentioned, the data provided by the technology provider are:

η=collector efficiency based on gross area.

η_0=0.567 for a gross area of a 180 m^2

IAM: incident angle modifier

$a_1 = 0\ W/m^2K$

$a_2 = 0.00034\ W/m^2K^2$

G_{bn}= Incident beam radiation on horizontal W/m^2

ΔT=average receiver fluid temperature above ambient air temperature

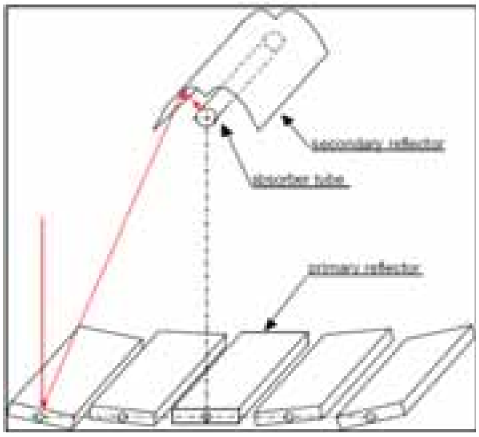

Figure 3 Linear Fresnel Collector

The analysis of the monitoring data collected in the Tunisian installation, where the length of the collector is significantly shorter resulting in a gross area of 120 m^2, resulted in the identification of the following collector parameters:

η_0=0.5, $a_1 = 3.9 * 10^{-7}$, $a_2 = 0$.

Considering that the end losses from a 120m^2, 16 m length collector are 5% more than those from a 180 m^2, 24m length collector [6]. The optical efficiency of the system analysed could be corrected to η_0=0.538 which matches fairly well (i.e., error of 7.5 %) with the value derived from the parameter identification.

The evacuated tube collector absorber is designed to work at high temperatures up to 400 °C. Thus for the moderate temperature range of operation used in this plant (below 185°C) the heat losses are relatively low, and the collector performance showed to be less sensitive to the loss coefficient a_1 and a_2.

2.2.2 Chiller

The chiller performance data acquired from the operation of the system during the period from May till August 2009 were analyzed; the chiller cooling power and thermal COP were correlated to the chiller operating parameters; the inlet and outlet temperatures flow rates as well as the ambient temperature.

A performance map for chiller performance predicting at different operating conditions has been created, validation of the outputs of the performance map against measured data is presented in Figure 4.

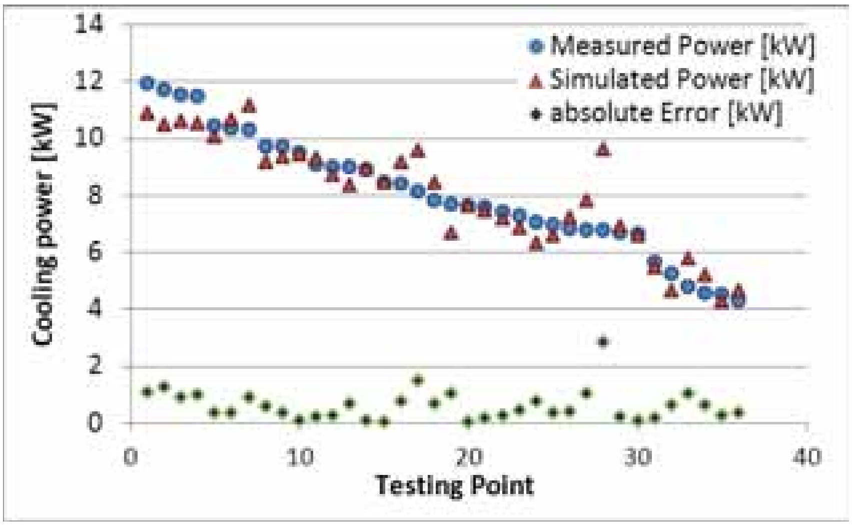

Figure 4 Validation of simulated against measured cooling power of the chiller at several operating points

2.3 System Optimization

The experimental activities aimed to to assess the characteristics and the performance of the main component of the system (as shown in the previous section) compared to their nominal behaviour. As well the monitoring data have been used for the whole system performance optimisation. The main monitored parameters are displayed in Figure.1.

As agreed within the international scientific community (i.e., Task 38 SHC-IEA) [9] one of the most representative performance figures for solar cooling systems assessment is the primary energy saving PE*saved*. In this section the primary energy saving PE*saved* is defined and the procedure to calculate it is presented.

Simulations were carried out to optimize system's operating parameters to ensure the highest primary energy savings of the system on annual bases. The main parameters studied are the solar loop pump control strategy and the chiller driving temperature. Compared to the parameter identification process presented in section 2.2, for an optimization process there is not a real system, and the filter is not required. The target function for ysim in this case was set to PE*saved*

2.3.1 Primary energy saving PE*saved*

To calculate the primary energy efficiency, the theoretical primary energy demand of a conventional reference system (PE*ref*) has to be calculated. Assumptions are, that all cold produced by the solar cooling system is produced by a compression chiller powered by electricity. Assuming seasonal performance factor SPF value of 2.5 for the reference chiller [7] and primary energy conversion factor for electricity production of $\varepsilon_{elec} = 0.4$ (kWh of electricity per kWh of primary energy) [8], the primary energy consumption of a reference systems PE*ref* can be calculated as:

$$PERref = \frac{Q_{solarcooling}}{SPF.\varepsilon_{elec}} \text{ [kWh]}$$

The solar system will also have a demand for electrical energy (solar collector motors, solar loop pump, chiller solution pump) which are highlighted in the system scheme in Figure 5. This consumption will be converted to PE as well, resulting in the Figure of primary energy consumed by the solar system PE*solar*.

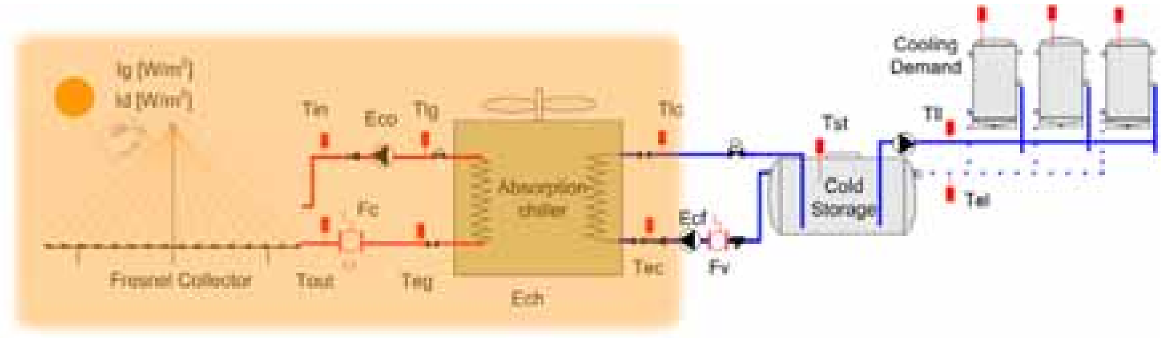

Figure 5 Solar cooling system scheme, highlighting the components considered for the primary energy consumption assessment.

The difference between both energy quantities is the saved primary energy PEsaved by the use of a solar system. The aim of the optimisation is to maximise this value.

$$PE_{saved} = PE_{ref} - PE_{solar} \qquad [kWh]$$

The measured electricity consumption of the absorption chiller and the solar loop pump is 900 W and 800W respectively. It has to be mentioned that the pressure drop in the generator of the prototype chiller used in this project is high, and this explains the high power consumption of the solar loop pump which have to overcome this high pressure drop.

2.3.1.1 Solar loop pump

As can be seen in the flow chart in Figure 6, the control of the solar loop pump can be either based on a scheduled operating hours “Time” mode, or based on the availability of the solar radiation “IR” mode;

- In “Time” control mode, the solar loop pump starts at tset1 in the morning, and shut down at tset2 in the evening *i.e.* (7 pm – 6 am).
- In “IR” mode, the solar radiation is measured and the value is compared to the starting set value “IRok”, the solar loop pump starts if the measured value is higher. Afterward, if the measured radiation value falls below the “IRok” due to sunset or clouds for a certain period “delay” the pump shuts down. A typical value of the delay period is 10 minutes to avoid frequent on of operation in cloudy days.

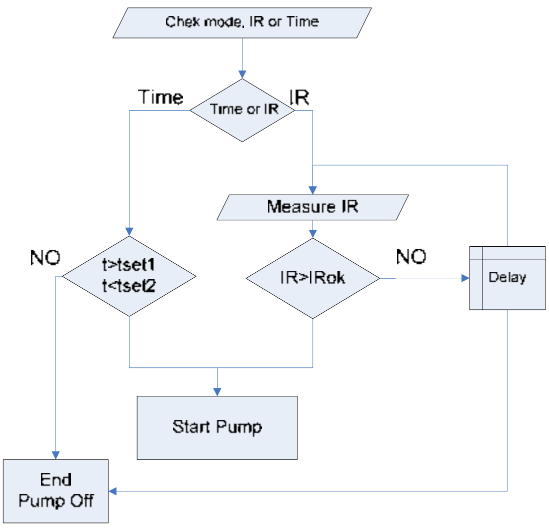

Figure 6 Control options of the solar loop pump

Two TRNSYS system simulation decks were created, one to simulate the system with “IR” control mode where the radiation level at which the chiller starts “IRok” and the hysteresis were defined as variables that could be varied by the optimization software GenOPT aiming at finding the highest energy savings. And the second was done to optimize the system with the “Time” control.

Simulation results showed that “Time” control mode results in a very small energy savings due to the fact that in winter months the solar pump works and consumes electricity, but the solar radiation is generally not enough to produce heat to run the chiller. And thus this consumed electricity is wasted.

This emphasizes the need to use the “IR” control mode to ensure that the solar pump works only if there is enough solar radiation that could heat the thermal fluid and be able to drive the absorption chiller.

Optimizing system’s performance controlled by “IR” control mode aims to find the radiation levels at which the system will start and stop while the primary energy saved will be highest. From figure 7, it’s clear that if the radiation level at which the system starts is low i.e. 200W/m^2, the collector pump will start earlier and the collector will produce more energy as well as the chiller, but the drawback is that the pump and the chiller will consume more electricity as well. On the other hand, if the system start at high radiation level i.e. 400W/m^2 then the electricity consumption by the pump will be less, but the collector and the chiller production will be less as well. And thus, an optimization process is required to find the starting radiation level at which the system will achieve the highest energy savings.

Applying the optimization algorithms, the optimum solar loop pump starting radiation “IRok” was found to be 340W/m^2. Figure 7 presents the simulation results for the operation of the system at different starting radiation levels, showing the optimum operation point. 7% and 20% increment in primary energy savings was achieved by running the system at the optimum operation point compared to starting at low radiation 200W/m^2 or high radiation 450 W/m^2 respectively.

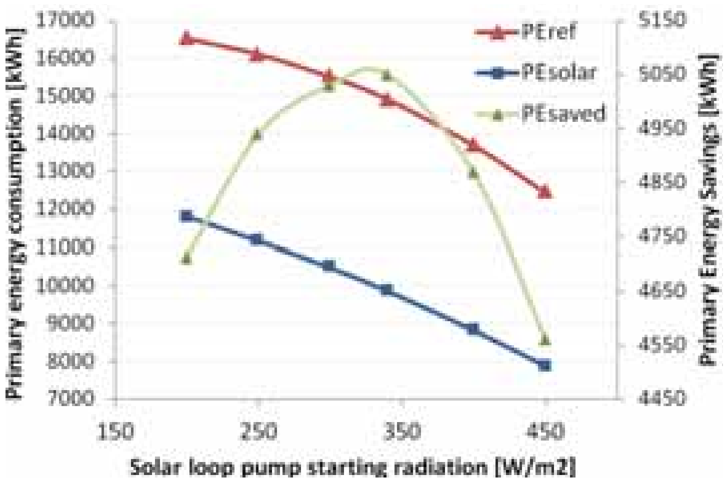

Figure 7 Primary energy consumption and savings at different solar loop pump starting radiation.

2.3.2 Chiller

The chiller starts its operation when the input temperature from the hot circuit is higher than the set temperature to start the chiller “tset”. The hot inlet temperature to the chiller's generator has a great influence on the performance of the chiller; and the higher this temperature is the better the performance of the chiller will be. Compared to other parameters that influence the performance of the chiller such as the ambient temperature, the hot inlet temperature is adjustable, and with the optimization process we are aiming to find the optimum hot starting temperature.

Considering one day, enabling the chiller to start at low starting temperature *i.e.* 100°C ensures that the chiller will start working early and will work for many hours. However, its performance will be low until the hot temperature will increase around midday. On the other hand, if the chiller is set to start at higher temperatures *i.e.* 160°C, the chiller will start later, but the chiller performance will be better for the shorter period of operation for that day.

This temperature was varied between (100°C-160°C) and through the optimization process it was found that the optimum starting temperature is 145°C as can be seen in Figure 9.

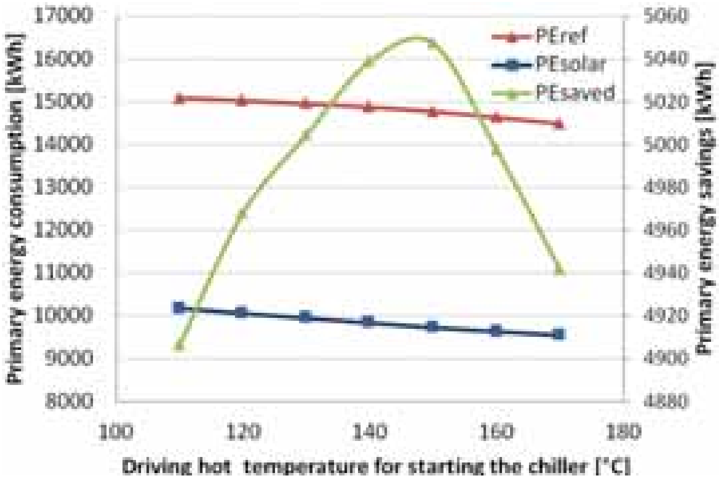

Figure 9 Primary energy consumption and savings at different driving hot temperatures for chiller starting.

2.4 Real system optimization

Based on the optimization process results, the control strategy of the system was updated from "Time" mode to "IR" mode in April 2010. Improvement in the system performance was clear to be noticed, as the electrical COP of the system was improved with 18% for May 2010 compared to May 2009 as can be seen in Figure 10.

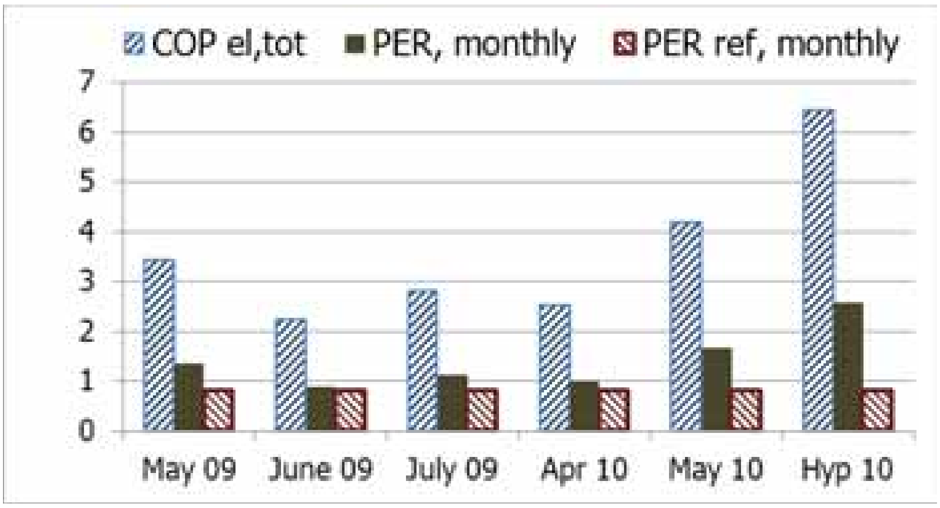

Figure 10 Electrical COP and primary energy ration for solar and reference systems for several months.

Recalling the point concerning the high electricity consumption in the solar loop pump, Considering the hydraulic improvement of the chiller' generator, and the removal of the monitoring equipments. The reduction in the pressure drop is supposed to reduce the electrical consumption of the solar loop pump by the half *i.e*. 400 W.

Simulating the system with this consumption characteristic of the solar pump improved the primary energy savings and the electrical COP of the system for 35% as shown for the hypothetical month in Figure 10.

3. Conclusion

The results of the experimental activities have been used for the validation of the mathematical models and for the system performance assessment. The validation process showed a good agreement of the chiller and the collector models with reality. The validated models were used to simulate the system in order to optimize its operating parameters, such as the chiller set temperatures for the hot circuits as well as the set radiation level to start and stop the solar pump.

As whole the study proofs that for food and agro industrial applications in areas with water scarcity and high direct radiation availability, the presented concept results technically viable and rentable from an energy point of view, and optimization process can improve the system even more. Simulations using validated models showed an optimization potential of 35% increase of the primary energy savings of the system.

4. References

[1] H-M. Henning, A. Häberle, A.Lodi, M. Motta, "Solar cooling and refrigeration with high temperature lifts – thermodynamic background and technical solution", – Proc. of 61st National ATI Congress, ATI-IIR International Session 'Solar Heating and Cooling', Perugia, (Italy), 14th September 2006.

[2] O. Ayadi, M. Motta, M. Aprile, "Assessment and Optimization of the Performance of a Novel Solar Refrigeration System Applied in Agro-Food Industry", Proc. of ISES Solar World Congress 2009, Johannesburg, South Africa 11-14 October 2009.

[3] M. Aprile, M. Motta, "Simulations of a novel solar absorption cooling concept: a comparison of static and dynamic system models", Proc. of 2nd International Conference Solar Air-Conditioning Otti, Tarragona, Spain 18-19 October 2007.

[4] J. Döll, T. Núñez , "Simulation of a Medium Scale Solar Cooling System for Industrial Processes", Proc. of 2nd International Conference Solar Air-Conditioning Otti, Tarragona, Spain 18-19 October 2007.

[5] Weiss W. and Rommel M. (2005) Medium Temperature Collectors. Gleisdorf: AEE INTEC.

[6] Bales C. (2001) "Parameter identification manual for TRNSYS models at SERC", Center for solar energy, Högskolan Dalarna, Publication Högskolan Dalarna 1650-1497 ; 2001:3DU-SERC--73--SE

[7] Häberle A. et al, (2007) "Fresnel Prozesswärmekollektor zur Solaren Kälteerzeugung", downloadable from http://www.dbu.de/ab/DBU-Abschlussbericht-AZ-23951.pdf

[8] Yu, F.W., and Chan, K.T "Advanced control of condensing temperature for enhancing the operating efficiency of air-cooled chillers." Building and Environment, Volume 40, Issue 6, June 2005, Pages 727-737

[9] Sparber W., Thuer A., Besana F., Streicher W., Henning H. M. "Unified Monitoring Procedure and Performance Assessment for Solar Assisted Heating and Cooling Systems" Proc. of 1st International Conference on Solar Heating, Cooling and Buildings, 7th - 10th October 2008, Lisbon, Portugal.