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Solar cooling systems utilizing concentrating solar collectors - An overview

Osama Ayadi[a,b*], Marcello Aprile[a], Mario Motta[a]

[a]*Department of Energy, Politecnico di Milano, Piazza L. da Vinci 32-20133 Milano, Italy*
[b]*Mechanical Engineering Department, The University of Jordan, Amman 11942, Jordan*

Abstract

The objective of this review article is to draw a picture about a promising solar cooling concept, based on the use of concentrating solar collectors, and to define the aspects that need to be considered in future developments. The following topics are covered: an overview of solar cooling systems utilizing concentrating solar collectors worldwide; the reasons behind the selection of these solar collection technologies for solar cooling applications; a quick assessment of the main performance figures for the different solar cooling schemes based on Monte Carlo simulations; the technical requirements of the technologies for future developments. Air-conditioning and refrigeration facilities driven by concentrating solar collectors are still infrequent and the outcomes of this review clearly present the small but steadily growing market of solar cooling systems coupled with concentrating solar collection technologies.

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Keywords: Solar assisted air-conditioning; solar cooling; concentrating solar collectors; simulations.

1. Introduction

By the end of 2011, about one thousand solar cooling systems were estimated to be installed worldwide [1]. While the majority of them utilized flat plate and evacuated tube collectors, less than thirty systems use single axis tracking concentrating (SATC) collectors to supply the heat required by the thermally driven cooling processes. The use of SATC collectors allows the production of heat at higher level of

* Corresponding author. Tel.: +962-65355000/22802; fax: +962-65300251.
E-mail address: o.ayadi@ju.edu.jo.

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temperatures compared to standard collection technologies used in buildings (i.e., flat plate collectors or evacuated tube collectors), matching the inlet temperature requested by highly efficient thermally driven chillers such as multi effect, liquid cooled, LiBr/water and GAX, air cooled, ammonia/water absorption chillers.

Nevertheless the implementation of such systems is not a novelty. The first demonstration of solar-assisted absorption cooling machine was made during the Paris World Exhibition in 1878 by Augustin Mouchot, based on a technique developed by Edmond Carré. This system has consisted of an ammonia/water absorption chiller and a parabolic reflector to produce ice [2].

Today, air-conditioning and refrigeration facilities driven by concentrating solar collectors are still infrequent. However, several test facilities using this technology have appeared in the literature during the last fifty years. In 1956, two small solar cooling systems with concentrating collectors were reported in Montlouis in France and in Flordia in US consisting of parabolic trough collectors coupled to prototype single stage water-ammonia absorption chillers [3]. A similar system configuration was reported few years later in Bangladesh in 1964 by the East Pakistan University of Engineering [4]. In 1979 a solar heating and cooling was reported in U.S. Army Yuma Proving Ground with a 1191 m^2 powered by parabolic through collectors (PTC) [5]. A solar cooling and heating system was installed in Sulaibiya in Kuwait in 1984 utilizing a prototoype PTC collectors and a single effect H_2O/LiBr absorption chiller from ARKLA (nowdays Robur) [6]. The Indian Institute of technology tested a small 0.25 k W chiller from Himalux, coupled to a 1.5 m^2 prototype PTC collector in 1989 [7]. The University of Jordan tested a prototype absorption chiller for air-conditioning by coupling the chiller to a prototype flat plate collector with a PTC collector in 1991 [8]; later, in 2000, a prototype PTC with an absorption chiller for refrigeration purpose in desert areas was tested [9]. Another study in 2000 was done by the Polytechnic University of Madrid on a prototype PTC collector using thermal oil as a heat transfer fluid coupled to a single effect ammonia/water absorption chiller [10]. Gee reported the first system of double effect absorption chiller coupled with PTC from Power RoofTM for air-conditioning application in North Carolina in USA in 2002 [11]. A solar cooling and heating system was installed in San Antonio (Texas) in USA in 2003 using 420 m2 of PTC collectors [12].

The recent years has witnessed a new growth of this system concept, as further discussed. While the systems reported in the period (1956-2003) were mainly for research purposes and utilized prototype concentrating collectors, the collectors used in the recent installations are mainly commercially available products. This fact is clearly linked to the expanding market of solar medium temperature collectors (temperature of heat production up to about 300°C), for applications such as industrial process heat. In the recent years, not only the number of the commercial suppliers of tracked process heat collectors increased about five-fold but also a remarkable variety of products has been developed [13].

Nomenclature

AC	Air-conditioning
COP_{th}	Thermal coefficient of performance (cooling power to heat input ratio)
DE	Double effect
DHW	Domestic hot water
EER	Energy efficiency ratio
E	Parasitic power consumption (J)
FP	Flat plate collector
PTC	Parabolic through collector
Q	Heat (J)
R	Refrigeration
SATC	Single axis tracking concentrating collector
SC	Solar cooling
SE	Single effect
SHC	Solar heating and cooling
TE	Triple effect

Suffixes

eva	Evaporator
gen	Generator
rej	Heat rejection
scs	Solar cooling system
sol	Solar heat collection system
sp	Solution pump

Greek letters

ε	Parasitic power consumption coefficient

2. Recent solar cooling systems utilizing concentrating collectors

A review list for systems installed after 2004 is presented in Table 1. Information about these systems was obtained from scientific papers, specialized publications, the web and direct contact with manufacturers. The configurations of the reviewed solar cooling systems utilizing concentrating solar collectors fall into one of the categories shown in Fig. 1.

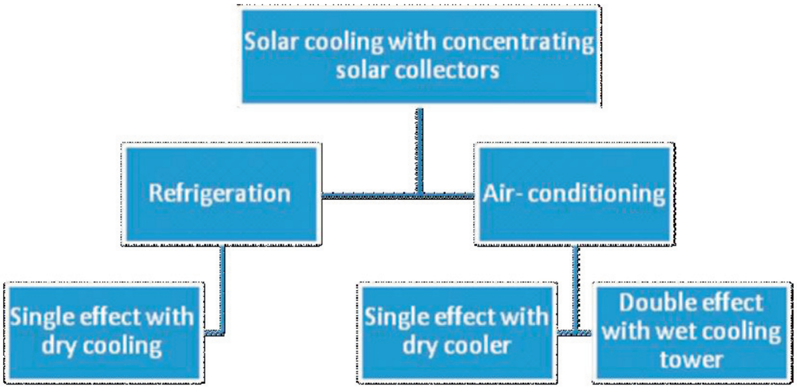

Fig. 1. Categories of high temperature solar cooling systems utilizing concentrating solar collectors

The majority (12) of the systems traced during the review consists of air-conditioning systems based on double effect, LiBr water absorption chillers employing a wet cooling tower. The second group (7) are systems based on single effect, air cooled, GAX water-ammonia chillers. Of these, nearly all (6) can produce cold refrigerant at negative temperatures, thus are suitable for (industrial) refrigeration. Remarkably, pressurized water is the mainly utilized heat transfer medium, on the hot side.

Table 1. Review of solar cooling systems utilizing concentrating collector (2004-present)

Collector producer	Location	Company or institution/ Application	Year	Aperture area (m2)	Fluid	Chiller type/Make/ Fluid pairs/Cooling power (kW)
Solitem						
1	Turkey / Dalman	Iberotel Sarigerme Park / SC, Steam	2004	360	Pressur. water	DE/Broad/LiBr-H2O/140
2	Turkey / Alanya	Grand Kaptan / SC	2005	360	Pressur. water	DE/Broad/LiBr-H2O/150
3	Turkey / Gebz	Gebz High technology Institute / SC, DHW	2008	324	Pressur. water	DE/Broad/LiBr-H2O/a
4	Turkey / Antalya	Metro / SHC	2008	432	Pressur. water	DE/Broad/LiBr-H2O/300
5	Jordan/ Dead sea	Dead Sea hotel / SC	2010	126	Pressur. water	SE/Robur/NH3-H2O/13
6	Turkey / Tarsus	FritolayPepsico / SC, steam	2008	1440	Pressur. water	a/a/a/420
7	Morocco / Casablanca	Moulay Youssef Hospital / SHC	2010	108	Thermal oil	SE/Robur/NH3-H2O/13

9	Firenze / Italy	Misericordia / SHC	2010	108	Saturated steam	SE/Robur/NH3-H2O/17
10	North republic of Cyprus	METU campus / SHC	2010	756	Pressur. water	SE/Thermax/LiBr-H2O/130
PSE						
11	Bergamo /Italy	Robur / SC	2006	132	Pressur. water	SE/Robur/NH3-H2O/13
12	Seville /Spain	Seville University / SHC	2007	354	Pressur. water	DE/Broad/LiBr-H2O/175
13	Grombalia/ Tunisia	Domaine Neferis / SC	2008	88	Pressur. water	SE/Robur/NH3-H2O/13
14	Abu Dhabi/UAE	Masdar /SC	2010	132 +334 PTC	Pressur. water	DE/Broad/LiBr-H2O/ 175
15	Qatar/ Doha	Showcase football stadium / SC	2010	1408	Pressur. water	DE/Thermax/LiBr-H2O/750
16	Freiburg/ Germany	PSE/ SC	2011	132	Pressur. water	SE/Robur/NH3-H2O/2*13
NEP						
17	Brisbane, QLD/Australia	Ipswich Hospital / SC	2007	570	Pressur. water	DE/Broad/LiBr-H2O/ 290
18	Padstow, NSW/ Australia,	SERDF Demo. Project / SC	2008	165	Pressur. water	DE/Broad/LiBr-H2O/ 175
19	Newcastle/ Australia	Cinema Complex /SC	2010	354	Pressur. water	DE/a/LiBr-H2O/230
21	Araluen, NT/ Australia	Art gallery /SC	2010	450	a	a/a/a/230
20	Newcastle/ Australia	(CSIRO) / SC	2007	50	Pressur. water	SE/ chillii®/LiBr-H2O/18
22	Long Island/NY/ USA	Piano factory / SC	2009	533	Pressur. water	DE/Broad/LiBr-H2O/315
23	Marrakech / Morocco	Lebonlait / SC	2010	78	Thermal oil	SE/Robur/NH3-H2O/13
Broad						
24	Pittsburgh/ USA	Carnegie Mellon University / SHC	2007	52	Pressur. water	DE/Broad/LiBr-H2O/16

3. Reasons for solar cooling based on SATC

The main reasons for employing concentrating collectors in solar cooling systems are: high efficient air-conditioning through coupling with double/triple effect chillers; and solar refrigeration serving industrial end-users, possibly in combination with process heat and steam.

In solar air-conditioning applications, one of the performance figures in use is given by the primary energy (PE) savings compared to a reference system. As consequence, the choice of the best configuration for a given application is often carried out targeting the highest PE saving achievable on a yearly base. The primary energy savings that could be reached with single stage absorption chillers (generally having a COP_{th} value around 0.6) are quite small. Thus, double and triple effect absorption chillers with higher COP_{th} (1.2 ÷ 1.4) are required for higher primary energy savings. However, double and triple effect chillers require high driving temperatures, which can be achieved by concentrating collectors working at these temperatures with reasonable efficiency. Moreover, in many cases, area restriction on roofs makes the utilization of single effect chillers with large flat plate or evacuated tube collectors not feasible. And this can be solved using double or triple effect absorption chillers with a concentrating collector.

Concerning industrial applications, several studies in the recent years highlighted that there is a high potential for refrigeration (temperatures below 0°C) in different areas of the globe (e.g., the Mediterranean [14], Central America [15]). However, this can be achieved by ammonia/ water absorption chillers requiring high temperature heat in input at the generator, in a range (120 ÷ 180 °C) which can only be satisfied by concentrating solar collectors. Moreover, several industrial applications require both cooling and steam for processes, and concentrating solar collectors can be very advantageous in the sense that their use is maximized.

In the following, an evaluation of the energy efficiency ratio (EER) of the different solar cooling concepts is achieved by means of Monte Carlo simulations. The potential is calculated on the basis of a simple algebraic model, in which several input parameters are independently varied within a given range, assuming normal distribution. The simulated outcome is a probabilistic distribution which provides insight on the expected energy savings (the mean) and the associated risk due to the uncertain evaluation of the input parameters (the standard deviation).

3.1. Solar cooling power consumption model

The generic solar cooling system comprises the solar heat collection system, the thermally driven chiller and the heat rejection device. For each subsystem, a thermal energy flow (Q) is used as the main driver for the calculation of the associated parasitic energy consumption (E). Namely: the cooling energy is the main driver for the electricity consumption due to the chilled water and solution pumps; the rejected heat is the main driver for the parasitic consumption of the cooling tower fan and pump, including head losses at condenser / absorber; the heat input at the generator is the main driver for the electricity consumption associated to the solar loop pump, including head losses at the generator. The relevant input parameters are the minimum and maximum values for the parasitic power coefficient of auxiliaries, i.e., solar loops pumps (ε_{sol}), generator head losses (ε_{gen}), chiller solution pump (ε_{sp}), chiller heat rejection system (ε_{rej}), evaporator head losses (ε_{eva}); and the thermal COP of the chiller.

According to this simplified modelling approach, the parasitic power consumption of the system can be derived through the following equations:

$$Q_{gen} = Q_{eva} / COP_{th} \quad (1)$$

$$Q_{rej} = Q_{eva} + Q_{gen} + E_{sp} \quad (2)$$

$$E_{sol} = \varepsilon_{sol} Q_{gen} \quad (3)$$

$$E_{gen} = \varepsilon_{gen} Q_{gen} \quad (4)$$

$$E_{sp} = \varepsilon_{sp} Q_{eva} \quad (5)$$

$$E_{rej} = \varepsilon_{rej} Q_{rej} \quad (6)$$

$$E_{eva} = \varepsilon_{eva} Q_{eva} \quad (7)$$

$$E_{scs} = E_{sol} + E_{gen} + E_{sp} + E_{rej} + E_{eva} \quad (8)$$

$$EER_{scs} = Q_{eva} / E_{scs} \quad (9)$$

3.2. Monte Carlo simulations

Following the modelling activities described in the previous section, five different system schemes have been analyzed:

- Flat plate (FP) collector coupled to single effect, water cooled, LiBr water chiller for air conditioning
- SATC collector coupled to single effect, air cooled, water ammonia chiller for air conditioning
- SATC collector coupled to double effect, water cooled, LiBr water chiller for air conditioning
- SATC collector coupled to triple effect, water cooled, LiBr water chiller for air conditioning
- SATC collector coupled to single effect, air cooled, water ammonia chiller for refrigeration

The values of the coefficients for the different analyzed systems have been estimated and/or retrieved from literature; they are reported in Table 2. The values are set for energy rather than power calculations, so they already account for inefficiencies due to heat losses, part load operation and cycling. Their derivation is based on both direct experience and simulation works.

Table 2. Simulation coefficients for the analyzed system schemes

Collector/Effect/Air(A) or Water (W) Cooled/Pair/Air Conditioning (AC) or Refrigereation (R)	ε_{sol}	ε_{gen}	ε_{sp}	ε_{rej}	ε_{eva}	COP_{th}
FP/SE/W/LiBr H2O/AC	2.0% ÷ 3.0%	1.0% ÷ 2.0%	0.1% ÷ 0.2%	2.5% ÷ 3.5%	1.0 ÷ 2.0	0.6 ÷ 0.7
SATC/SE/A/H2O NH3/AC	3.0% ÷ 4.0%	1.0% ÷ 2.0%	0.7% ÷ 1.0%	1.0% ÷ 2.0%	1.2 ÷ 2.4	0.6 ÷ 0.7
SATC/DE/W/LiBr H2O/AC	3.0% ÷ 4.0%	1.0% ÷ 2.0%	0.2% ÷ 0.3%	2.5% ÷ 3.5%	1.0 ÷ 2.0	0.9 ÷ 1.2
SATC/TE/W/LiBr H2O/AC	3.5% ÷ 4.5%	1.0% ÷ 2.0%	0.3% ÷ 0.4%	2.5% ÷ 3.5%	1.0 ÷ 2.0	1.2 ÷ 1.5
SATC/SE/A/H2O NH3/R	3.0% ÷ 4.0%	1.0% ÷ 2.0%	1.0% ÷ 1.3%	2.0% ÷ 3.0%	1.2 ÷ 2.4	0.5 ÷ 0.7

The distribution resulting for the total energy efficiency ratio (EER_{scs}) of each solar cooling system is shown in Fig. 2.

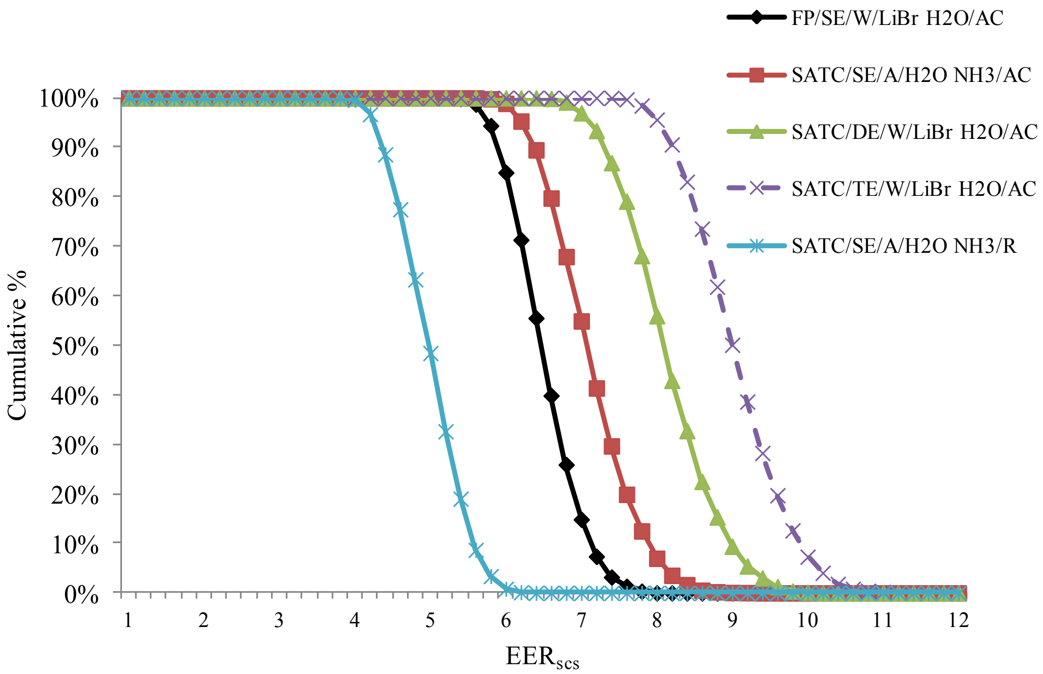

Fig. 2. Cumulative probability for the EER_{scs} of the analyzed system schemes

The flat plate collector coupled to single effect, water cooled, LiBr water chiller for air conditioning (FP/SE/W/LiBr H2O/AC) is the reference system here. Compared to the reference, system SATC/SE/A/H2O NH3/AC performs better, with an average EER_{scs} of about 7. This is mainly due to a lower parasitic consumption for heat rejection. It shall be remarked that the system is air cooled, thus more suitable than the reference to applications where water is scarce. When a wet cooling tower can be used, system SATC/DE/W/LiBr H2O/AC can perform even better, with an average EER_{scs} above 8. A triple effect chiller (system SATC/TE/W/LiBr H2O/AC) would reach an average EER_{scs} above 9, although the high driving temperature (> 250 °C) would pose the problem of the selection of the heat transfer medium. When refrigeration below 0 °C is needed, the only possibility is system SATC/SE/A/H2O NH3/R. Due to the high temperature lift of the application, this system can reach an average EER_{scs} of about 5. However, this value shall be compared to that of an equivalent vapour compression system providing refrigeration at the same temperature, thus the estimated performance can be considered very efficient.

4. Conclusion

The presented overview of solar cooling systems using concentrating collectors has shown that, starting from year 2004, the number of installations is growing and the recent installations make use of commercially available collectors (single tracking axis, i.e. PTC and Fresnel) and thermally driven chillers (double effect LiBr water and single effect water ammonia). The different systems can be classified in a few categories, namely: single effect with dry cooler, for air conditioning or refrigeration, and double effect with wet cooling tower for air conditioning only. A simple analysis based on Monte Carlo simulations has shown that, assuming good design, installation and control, the expected EER of the whole system is attractive for each application. In air conditioning, best performances are achieved with wet cooled multi effect LiBr water chillers. In such systems, parasitic consumption associated to heat to solar heat collection becomes relatively important. This is even more important for single effect dry cooled GAX water ammonia, which is the solution for both air conditioning and refrigeration in areas where cooling water is not available. Therefore, in future developments, ways to decrease the parasitic consumption of the solar loop during warming up and chiller operation shall be looked for. Possible solutions include: variable speed control of solar pumps, better design of the generator heat exchanger and, in industrial application, direct steam generation.

References

[1] Henning H-M. Status and Perspectives of Solar Air-Conditioning and Refrigeration. OTTI 4th international conference solar air-conditioning 2011;18-33.

[2] Mouchot A, Weber R. Die Sonnenwärme und ihre industriellen Anwendungen. Oberbözberg, Schweiz: Olynthus, 1987.

[3] Trombe F. and Foex M. The production of cold by means of solar radiation. *Solar Energy* 1957; 1(1): 51-52.

[4] Desa V. Experiments with solar-energy utilization at Dacca. Solar Energy 1964; 8(3):83-90.

[5] Fernández-García A. et al. Parabolic-trough solar collectors and their applications. *Renewable and Sustainable Energy Reviews* 2010; 14(7): 1695-1721.

[6] Osman M. Performance analysis and load matching for tracking cylindrical parabolic collectors for solar cooling in arid zones. *Energy Conversion and Management* 1985; 25(3): 295-302.

[7] Raheman H and Gupta C.R.. Development of a Solar-Energy-Operated Vapour-Absorption-Type Refrigerator. *Applied Energy* 1989; 34:89-98.

[8] Hammad M and Audi M. Performance of a solar LiBr-water absorption refrigeration system. *Renewable Energy* 1992; 2(3):275-282.

[9] Hammad M and Habali S. Design and performance study of a solar energy powered vaccine cabinet. *Applied Thermal Engineering* 2000; 20(18):1785-1798.

[10] De Francisco A. et al. Development and testing of a prototype of low-power water–ammonia absorption equipment for solar energy applications. *Renewable Energy* 2002; 25(4): 537-544.

[11] NREL. Heating Water with Solar Energy Costs Less at the Phoenix Federal Correctional Institution. DOE/GO-102004-1914 2004.

[12] Gee RC. Solar powering of high efficiency absorption chiller. 2004. Available at:
http://www.osti.gov/bridge/product.biblio.jsp?query_id=0&page=0&osti_id=840264&Row=0 [Accessed May 2, 2011].

[13] Mohart A.Solar process heat is becoming sexy. *Sun & wind energy* 2011; 70-77.

[14] Ayadi O, Aprile M, Motta M. Assessment and Optimization of the Performance of a Novel Solar Refrigeration System Applied in Agro-Food Industry. In: ISES Solar World Congress 2009. Johannesburg, South Africa, 11/10/2009-14/10/2009, 687-695.

[15] Roberto Best B., Juan M. Aceves H., Jorge M. Islas S., Fabio L. Manzini P., Isaac Pilatowsky F., Rossano Scoccia, Mario Motta, Solar cooling in the food industry in Mexico: A case study, Applied Thermal Engineering, Available online 28 December 2011, ISSN 1359-4311