

SOLAR COOLING IN MADRID: EXPERIMENTAL RESULTS OBTAINED TO PARTIAL LOAD DURING 2003 SUMMER

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Abstract: This paper provides experimental results derived through field testing of a partial load solar energized cooling system in Madrid during the summer period of 2003. Solar hot water was delivered by means of a 50 m² array of flat-plate collectors to drive a single-effect (LiBr/H₂O) absorption chiller of 35 kW nominal cooling capacity. Thermal energy was stored in a 2 m³ stratified hot water storage tank during hours of bright sunshine. Chilled water produced at the evaporator was supplied to a fan coil units and the heat of condensation and absorption was rejected by means of a forced draft cooling tower. Instantaneous, daily and period energy flows and energy balance in the installation is presented. Peak insolation of 969 Wm⁻² (at 12:30 solar time on 08/08/03) produced 5.13 kW of cooling at a solar to cooling conversion efficiency of 11%. Maximum cooling capacity was 7.5 kW. Cooling was provided for 8.67 hours and the chiller required a threshold insolation of 711 Wm⁻² for start-up and 373 Wm⁻² for shut-down.

Keywords: Solar Cooling ; Absorption ; Partial Load ; Flat-Plate Collectors ; Thermal Storage

1. INTRODUCTION

The incidence of solar energy and cooling requirements are approximately in phase, which makes solar cooling an attractive alternative to conventional electric cooling in modern buildings. Some investigators have demonstrated solar air-conditioning by energizing single-

effect (LiBr/H₂O) absorption machines with heat of flat-plate collectors operating between 70°C to 90°C [1-5]. Technological improvements in collector and cooling cycle designs over the years have created an opportunity to realize higher system performances. When the Sun is used as the only heat source with thermal storage, these systems are characterized as having high collector efficiency, part load operation, high COP [6] and long daily cooling periods. Higher COP, cooling capacity and longer daily cooling periods can be achieved with evacuated tube collector systems operating up to 170°C with reasonable efficiencies [7, 8]. However, their life-cycle costs are much higher than a conventional chiller system [9].

In what follows, the whole experimental facility and individual system components are described with the methodology used for testing under real time conditions. Results, discussion and energy balance analysis is then presented.

2. DESCRIPTION OF THE EXPERIMENTAL PLANT

Fig. 1 shows a schematic of the experimental solar absorption air-conditioning system consisting of four main water streams flowing through the generator, evaporator, condenser and absorber. Circulating hot water through the flat-plate collector panels are heated to about 90°C by the incident solar energy on the copper absorber plates. The heat produced is transferred to a storage tank via a plate heat exchanger. At about 80°C prevailing at the top of the tank, heat is supplied to the generator of the absorption machine, which operates in vacuum. This is to boil a weak solution of solvent and refrigerant (lithium bromide and water), that results in a strong solution. The refrigerant vapour is condensed on the condenser tubes. The condensate is throttled through an expansion device obtaining two-phase refrigerant; the liquid refrigerant evaporates under low pressure in the evaporator, thus producing cooling. Chilled water flowing through the evaporator tubes is supplied to the fan coil units at about 8°C. Thermal energy was supplied entirely by solar collectors.

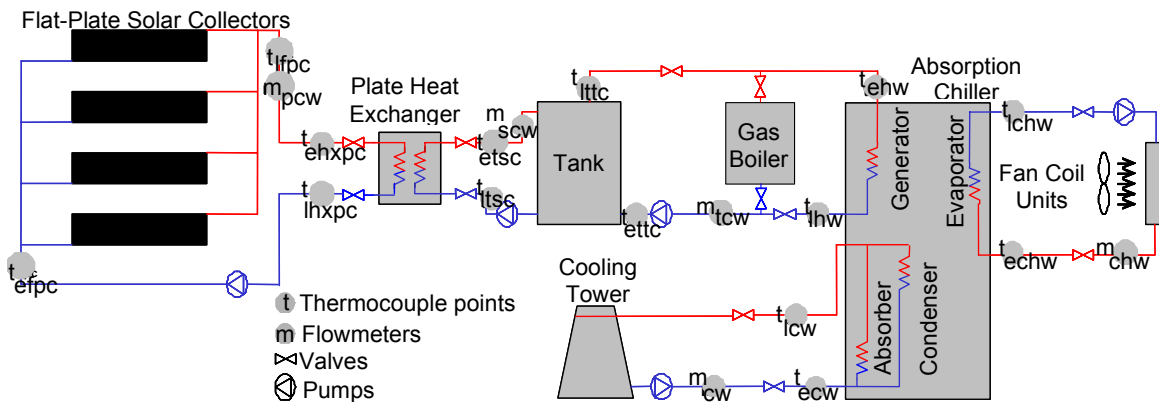


Fig. 1. The Carlos III University solar cooling scheme.

A solar powered air-conditioning system has been recently put into operation at Carlos III University of Madrid to demonstrate solar powered cooling, using commercial components. It was funded by a combined action between the Spanish Ministry of Industry, the local government of Madrid (Comunidad Autónoma de Madrid), the Carlos III University and the Instituto Eduardo Torroja de Ciencias de la Construcción (IETcc), belonging to CSIC. Twenty flat-plate collector modules with an absorber area of 2.5 m² each were used to energize the system. Fig. 2 shows a view of the collector array and Figs. 3(a) to (d), show the absorption chiller, cooling tower, storage tank and plate heat exchanger.



Fig. 2. View of the flat-plate solar collector array installed in UC3M Leganés Campus.

The use of a hot water tank between the collector and the absorption machine has been reported to yield higher system efficiency [5] and extends the daily cooling period. It also prevents cycling of the absorption machine due to variations in solar radiation intensity. The useful solar heat input to the tank was determined with the measured flow rate in the secondary hot water circuit (between the plate heat exchanger and the tank) and the temperature difference across the inlet and outlet of the tank by applying. To minimize the tank loss, a fiberglass insulating material with a thickness of 50mm to 60mm has been recommended, which yields an overall heat loss coefficient (U value) of $0.5 \text{ Wm}^{-2} \text{ }^{\circ}\text{C}$ to $0.9 \text{ Wm}^{-2} \text{ }^{\circ}\text{C}$. The Yazaki [10] chiller has a nominal cooling capacity of 35 kW at the following operating conditions:

Entering / leaving hot water temperature = $88^{\circ}\text{C} / 83^{\circ}\text{C}$ (at flow rate: 2.4 ls^{-1})

Entering / leaving cooling water temperature = $29.5^{\circ}\text{C} / 34.5^{\circ}\text{C}$ (at flow rate: 4.0 ls^{-1})

Leaving / entering chilled water temperature = $9^{\circ}\text{C} / 14^{\circ}\text{C}$ (at flow rate: 1.7 ls^{-1}).

A fan coil unit (FCU) of 10 kW cooling capacity (28.6% of nominal capacity) was used to supply cold air into the laboratory space. The cooling coil was directly connected to the evaporator. The chilled water temperature was kept within 7°C to 10°C by thermostatic control. Measured chilled water flow rate was about 0.29 ls^{-1} .

A cooling tower was used for rejecting the heat of absorption and condensation and supplied cooling water to the absorber and condenser. The measured flow rate of cooling water delivered by the absorber-condenser pumps was approximately 0.81 ls^{-1} . The refrigeration coefficient of performance (COP) was determined from the ratio of the evaporator load and generator load:

$$\text{COP} = \frac{Q_e}{Q_g} \quad (1)$$

A plate heat exchanger located in the tank room was used to separate the primary and secondary water circuits.

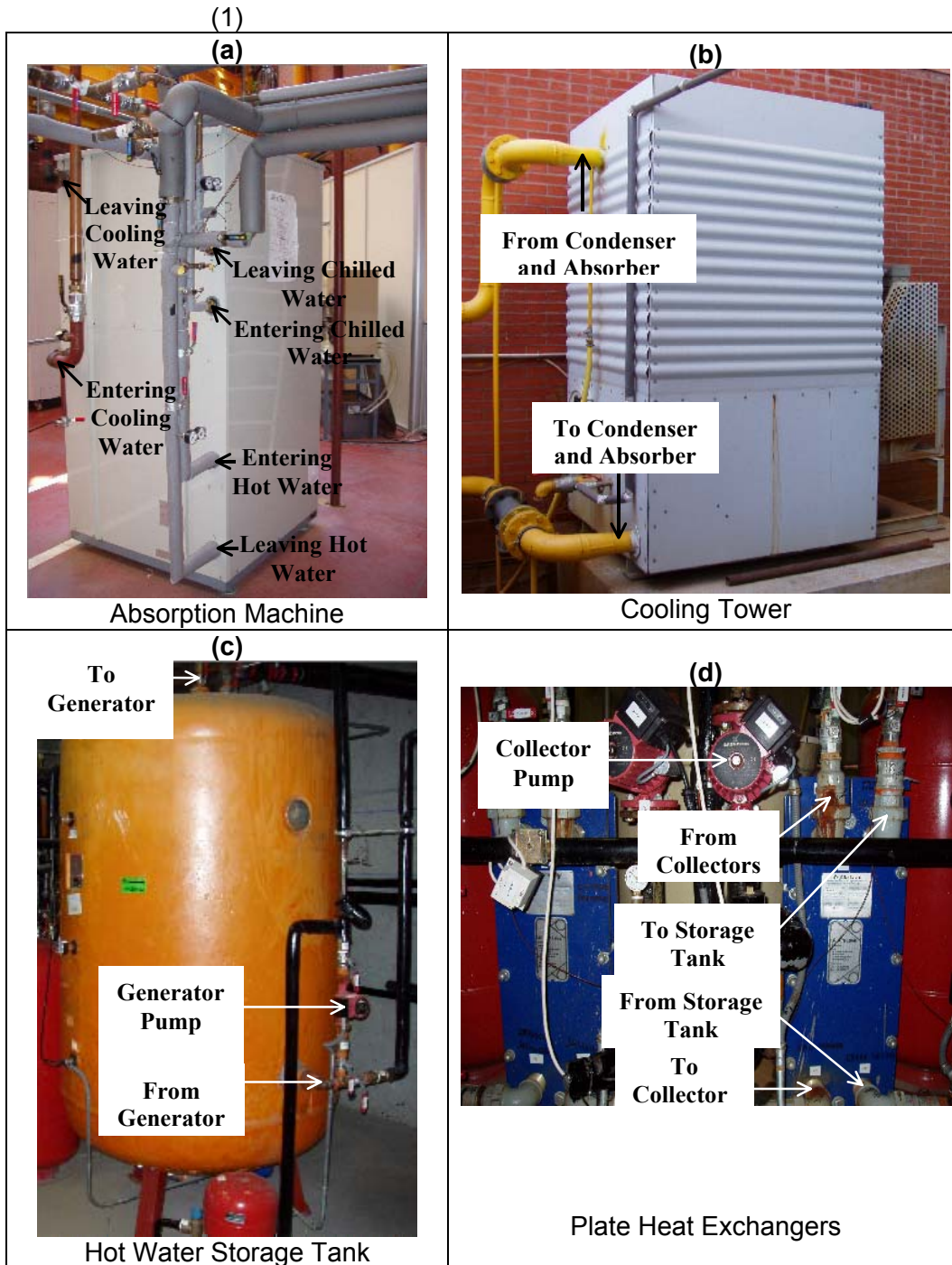


Fig. 3. (a) Absorption chiller ; (b) Cooling tower ; (c) Storage tank ; (d) Plate heat exchanger

3. RESULTS AND DISCUSSION

The solar cooling system was tested daily from the 25th of July till the 19th of August 2003. During these days, the sky in Madrid was generally clear, thus ideal for solar cooling and permitted the use of clear sky models for the calculation of tilted insolation from the horizontal pyranometer. In the present work, data from a hot sunny day on the 8th of August 2003 is

presented in detail. This is because on this day, the highest cooling energy of 40 kWh day⁻¹ was produced. The daily energy quantities in the installation are given on fig. 4 and Table 1. Fig. 6 displays the global result of operating the cooling system with solar energy. The absorption unit was operated from 09:40 to 18:20, a total 8 hours and 40 minutes. This describes a typical day of solar cooling in Madrid.

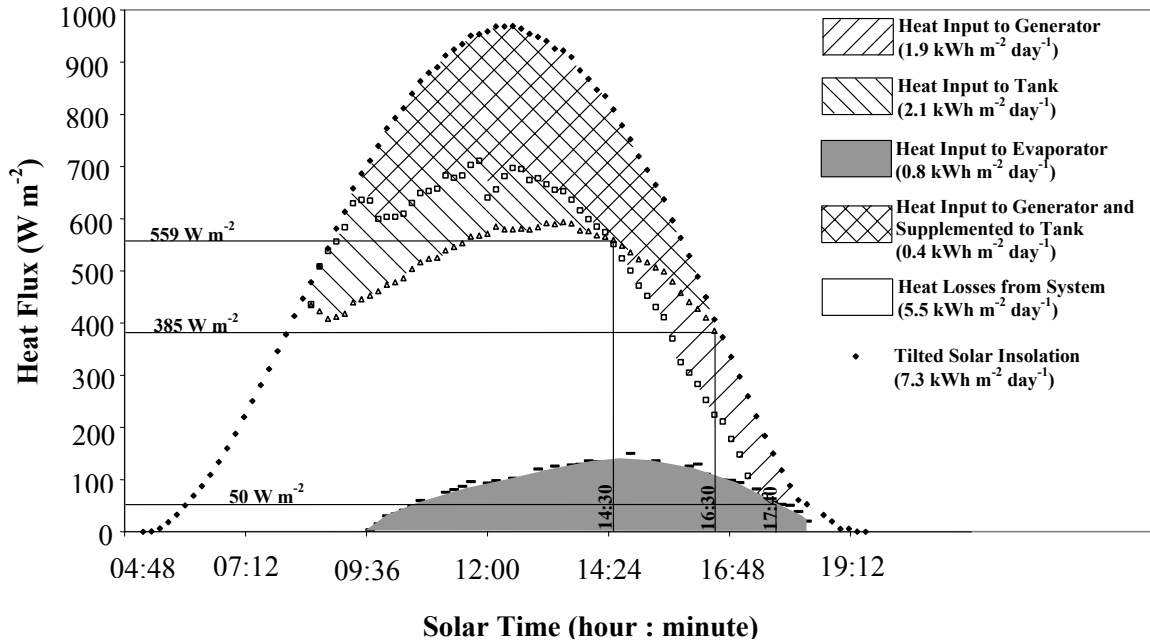


Fig. 4. Heat flows in the system for 08 August 2003

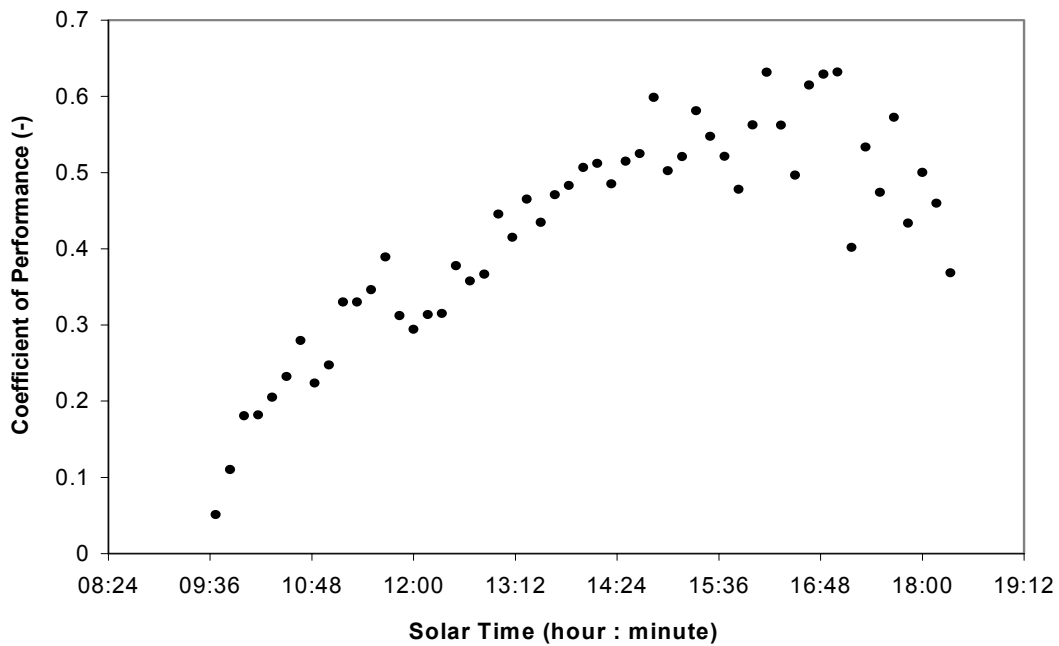


Fig. 5. Coefficient of performance of absorption refrigeration process for 08 August 2003

Fig. 5 displays the refrigeration coefficient of performance obtained by applying eq. (1), which varied from as low as 0.05 at the start of the cooling period to 0.63 at 17:00 on 08/08/03. The average COP for the day was 0.42.

4.ENERGY BALANCE FOR THE INSTALLATION

Table 1 shows the daily energy balance for the installation during the entire monitoring period. The data consists essentially of 12 parameters relating to energy flows for the 49.9 m² of collector (absorber) area in addition to efficiency measures. The minimum to maximum daily values of these parameters are as follows:

Table 1. Daily and period energy balance for the solar cooling system

July-Aug. 2003	Daily solar energy (kWh day ⁻¹)	Daily cooling, Q _e (kWh day ⁻¹)	Daily input heat to generator, Q _g (kWh day ⁻¹)	Daily chiller COP	Daily collector efficiency Q _g / G _T
25	366.7	35.0	99.5	0.35	0.27
26	355.3	26.9	92.2	0.29	0.26
27	357.3	23.0	95.0	0.24	0.27
29	353.2	26.9	94.5	0.28	0.27
30	328.5	30.6	84.1	0.36	0.26
31	358.0	32.6	87.3	0.37	0.24
2	321.3	31.9	86.9	0.37	0.27
5	342.9	34.8	90.5	0.38	0.26
6	354.7	33.6	84.1	0.40	0.24
8	364.1	40.0	95.9	0.42	0.26
10	326.0	25.4	73.3	0.35	0.22
11	344.3	35.3	87.1	0.41	0.25
12	348.7	24.4	83.2	0.29	0.24
13	349.3	21.2	92.1	0.23	0.26
14	328.0	18.2	69.8	0.26	0.21
15	329.2	19.3	79.5	0.24	0.24
16	336.1	35.2	85.6	0.41	0.25
17	346.5	26.6	83.7	0.32	0.24
18	376.3	38.9	94.6	0.41	0.25
19	354.9	37.6	91.3	0.41	0.26
Period Ave.	347.1	29.9	87.5	0.34	0.25

5.CONCLUSIONS

A solar cooling system consisting of a flat-plate collector array, absorption machine, cooling tower and hot water storage tank was demonstrated under real time conditions in Leganés 20 km Southwest of Madrid. The system worked entirely with solar energy and produced chilled water for 7.33 hours (under permanent regime) on a hot day of 8th August 2003. For 08th August 2003, the daily efficiencies obtained are as follows:

Daily average ratio of heat input to tank and solar insolation was 0.29.

Daily average ratio of heat input to generator and solar insolation was 0.26.

Daily average COP was 0.42.

Daily average solar cooling ratio was 0.11.

Over the period of monitoring (25/07 to 19/08, 20 days), the following results were achieved:

Total solar energy intercepted was 139 kWh m⁻².

Total solar energy supplied to the generator was 35.1 kWh m⁻².

Total cold produced was 12 kWh m⁻²

Period average refrigeration COP was 0.34.

Period average solar cooling ratio was 0.09.

ACKNOWLEDGEMENTS

The authors are especially grateful to ATYCA Program of the Ministerio de Industria of Spain, the Consejería de Medioambiente de la Comunidad de Madrid to as well as the valuable help of Emilio Martin of IETcc.

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NOMENCLATURE

COP Coefficient of Performance

Q Heat

Subscripts

e evaporator

g generator