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Performance and Operational Experiences of Solar Driven Cooling Plant after Five Years in Operation

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Abstract

The main aim of this study is to report the performance evaluation as well as the gained operational experiences of a solar-driven cooling plant after 5 years in operation, in addition, based on the gained experiences, a suggestion for an appropriate small-scale solar-driven cooling plant for hot arid areas is presented. The plant includes a 35.17 KW cooling (10-RT) absorption chiller, vacuum tubes collectors with gross and net areas of 108 m^2 and 72 m^2, a hot water storage capacity of 6.8 m^3, a cold water storage capacity of 1.5 m^3 and a 134 kW cooling tower. The plant provides air-conditioning for a floor space of 270 m^2. The plant performance results indicate: instead small solar energy values at the plant location, the daily solar fraction ranged from 0.33 to 0.41, and for the duration from August 2002 to November 2007 the total solar energy supplied to the chiller is 53914 kWh and the total external energy (gas energy) supplied to the chiller is 35249 kWh and their percentage are about 60% and 40%, respectively. The collectors' filed instantaneous mean efficiency value is about 0.63, the monthly average value varies from 34.1 % up to 41.8 %, with a five-year average value of 28.3 %, respectively and the daily chiller COP varies from 0.37 to 0.81, respectively. The gained from the operational experiences are: in hot arid areas, the water normally is rare, thus the re-cooling system should be designed based on dry re-cooling techniques. Moreover, based on the total initial capital cost of the entire solar cooling system, adsorption-cooling technology for small-scale solar-driven air-conditioning systems is the most appropriate. This is because these chillers can be driven by a low temperature energy source that can be obtained from flat plate collectors where, costs are a bit lower for flat plate collectors with liquid heat transfer carrier.

Keywords: *Solar cooling; Absorption chillers; Lithium bromide-water; operational experiences*

1. Introduction

In fact, most of the buildings' cooling demands in summer are associated with high solar energy availability, which offers an opportunity to further exploit solar energy for cooling. Thermally driven refrigeration systems are providing cold energy by using heat as motive energy. This heat can be obtained from combined heat and power systems, waste heat sources or solar energy. There are numerous prototypes and demonstration solar driven cooling plants have been erected world wide. Several techniques and concepts are currently discussed and there are remain high research and development necessity. In addition, there are also first operational experiences gathered by the existing plants. Thus for further development of solar cooling and implementation of these systems into the market, it is important to evaluate and interpret the available gained operational experiences form a real working plant. Moreover, solar cooling technology provides an important contribution to both economical and ecological energy supply. Throughout the literature, there are numerous studies reporting the performance of solar driven single-effect lithium bromide-water (LiBr-H_2O) chiller. Syed et al. [1] reported the performance of a LiBr-H_2O absorption chiller with 35.17 KW (10-RT) nominal cooling capacity that driven by hot water from 49.9 m^2 flat plate collectors and integrated with 2 m^3 hot water storage tank. The plant is installed at a typical Spanish house in Madrid. Zambrano [2] presented results of a solar absorption cooling plant which has 35.17 KW nominal cooling capacity at Seville in Spain. The plant has flat collectors with a total area of 151 m^2, a 2.5 m^3 hot water storage tank and an auxiliary gas heating system. Thepa et al. [3] designed and installed a 35.17 KW cooling (10-RT) solar-driven absorption cooling system in Thailand in 2005.

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The system has a 0.4 m^3 hot water storage tank and 72 m^2 evacuated tube solar collectors that delivered a yearly average solar heating fraction of 81 %. In addition to these current solar operated lithium bromide-water absorption chillers for space air-conditioning application, there are many other pilot or demonstration plants working in different locations worldwide having a solar heating fraction up to 81 % with different COP values. However, it is found that no information have been published so far concerning the gained operational experiences from solar powered single effect lithium bromide-water absorption cooling system. Ali et al. [4] and [5] reported the performance evaluation of an integrated cooling plant having both free cooling system and solar-powered single-effect lithium bromide-water absorption chiller in operation for more than 7 years. The plant is used to provide air-conditioning for a floor space of 270 m^2, and it is a part of the infrastructure at Fraunhofer Institute UMSICHT in Oberhausen, Germany. The plant was driven by solar energy only from year 2002 to 2004 under the typical weather conditions in the Central Europe. From year 2005 until now, the plant has been integrated with the institute heating system that can provide solar heating portion in heating season. Moreover, it can utilize the available hot water of the Institute heating system (gas boiler and micro gas turbine) as supplementary source, in case the solar collector field supply heat is not enough, to drive the chiller during cooling season.

The main aim of this study is to report the performance evaluation as well as the gained operational experiences of a solar driven cooling plant after 5 years in operation, in addition, based on the gained experiences, a suggestion for an appropriate small-scale solar- driven cooling plant for hot arid areas is presented.

2. Plant Description, Measurements, Data Acquisition and Processing System

An integrated cooling plant with both combined free cooling and solar-driven absorption chiller provides the cooling demands for the Fraunhofer Institute (UMSICHT) in Oberhausen-Germany (51° 28' N latitude and 6° 51' E longitude), laboratories, meeting rooms and three offices during the cooling season. Figure (1) shows the plant schematic diagram. In which, the major components of the plant are a roof-mounted vacuum tubes solar collector, a 35.17 KW cooling (10-RT) single-effect LiBr-H_2O absorption chiller, a hot water storage tank, a cold water storage tank, a cooling tower, a free cooling heat exchanger, a roof top heat release heat exchanger, pumps, a control system, a water treatment system, a pressure maintaining system and some other auxiliary equipments. In addition, it is comprised of four main flow circuits which are the solar circuit (with anti-freezing agent), the hot water circuit, the chilled water circuit, and the cooling water circuit. These circuits interrelate with the absorption chillers at the generator, the evaporator, the absorber and the condenser, respectively. While both the cooling water and chilled water circuits are interrelate at the free cooling heat exchanger as shown in Figure (1). In addition, the solar circuit is connected to the hot water circuit by a plate type heat exchanger HE1. The solar collector field is composed of a 108 m^2 apparent area and a 72 m^2 absorbing area for an array of 432 evacuated tubes in 9 collector fields which work in the range of 97/105 °C and a capacity of 50 kW (for I=1000 W/m^2), where I is the solar insolation at the collector plane. A Water Fired Chiller (WFC-10 RT) with a rated capacity of 35.17 KW cooling (10-RT) when operating at a driving hot water temperature of 87 °C, coolant water temperature of 29.5 °C and output chilled at 9 °C with coefficient of performance

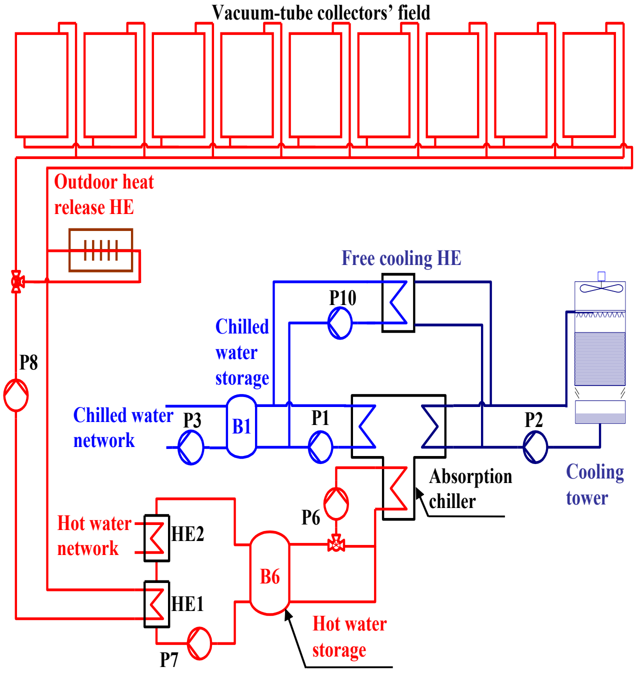


Fig. 1 A schematic diagram of the cooling plant, where B is storage tank, HE is heat exchanger and P is pump, respectively.

(COP) of 0.7 as reported by the manufacture. The cooling tower is located at the rooftop of the building with a capacity of 134 kW at 24/31 °C when ambient air wet-bulb temperature is 21 oC. The thermal buffer system is composed of two tanks. The first is the hot water storage tank, B6, as shown in Figure (1) with a capacity of 6.8 m^3. The second tank is the cold-water storage buffer with a capacity of 1.5 m^3, B1, as shown in Figure (1). A floor space of about 270 m^2 is air-conditioned by this plant.

The load network is distributed into a central air-handling unit, which provides 100 % fresh air to labs, several air cooler units at offices and convective radiators at the central computers labs of the institute. The chilled water is supplied to each of these loads installations via a supply network with a length of about 390m. The volume flow rate at six different locations in the plant is measured by different water meters. Multi-jet dry dial vane impeller hot water meters are used in solar circuit and hot water circuit with a measuring range from 0.2 to 20 m^3/h. While, the woltmann water meters are used in the re-cooling circuit and the chilled water system with a measuring range from 0.45 to 90 m^3/h, and multi-jet water meters are used for tap up water and waste water with a measuring range from 0.05 to 5 m^3/h, respectively. The temperatures were measured with PT-1000 sensors in protection sleeves, with measuring ranges of 0-60 °C for chilled water and re-cooling water, 0-150 °C for hot water and 0-200 °C for the solar circuit, respectively. The resolution of the temperature measurement is 0.01 °C. The incident total solar radiation on the plane of the solar collector absorber level was measured by a Tritec Spectrum Irradiation Sensor 300 having a measuring range of 0-1500 W/m2, with a standard 4-20 mA-signal output. The relative measurement error amounts corresponding to the statements by the manufacturers varied from 1% to 5%. Different pumps were used to circulate the fluids in each circuit as shown in Figure

(1). In addition, flow-controlling valves integrated with plant controller system were used to adjust the flow rates.

3. Presentation of Parameters

From the measured data, the results are presented based on using a simple data reduction. The thermal capacity of the equipments is determined by:

$$Q = \dot{m} \cdot c_p \cdot \Delta T \quad \text{kW} \qquad (1)$$

where $\dot{m}$ is the mass flow rate in kg/s, c_p is the specific heat at constant pressure in kJ/(kg.C) and ΔT is the temperature difference in ^{o}C, respectively. The energy during a certain period is determined by the integration of the capacity during this time as follows:

$$E = \int_{to}^{tf} Q \cdot dt \quad \text{kWh} \qquad (2)$$

where t_0 and t_f are the initial and final times. The solar collectors' efficiency (η) is determined by:

$$\eta = \frac{Q_{solar,net}}{I \cdot A_{absorber}} \qquad (3)$$

where $Q_{solar,net}$ is the net thermal power gained by the water from the collectors' field, I is the solar radiation in the collector absorber plane and $A_{absorber}$ is the total absorbing area of the collectors' field, respectively. Neglecting the chiller pump power, the chiller coefficient of performance, COP, is defined as the ratio of the evaporator cold capacity Q_E to the heat input to generator Q_G as follows:

$$COP = \frac{Q_E}{Q_G} \qquad (4)$$

4. Results and Discussions

There have been enormous amounts of recorded measured data from the plant since its installation in August 2002. However, samples from these measurements are used to extract the results in this contribution, which are in some cases series of results or represent the average values of five years' duration for the plant operation.

4.1. Solar Energy Heat Fraction and Collector Performance

The monthly total incident solar energy at collector absorber level per meter square is shown in Figure (2). As can be seen from the figure, the values are small, about one third, when compared with similar values in hot arid areas. Instead of these low solar energy values, the plant is erected and in operation to provide the required cooling for the Institute buildings. From the measured data, clearly, the solar fraction in motive energy of the chiller is high. The fraction of the total driving heat load, which is covered by solar energy, is referred as solar heat fraction. Instead of these small solar energy values shown in Figure (2), it is found that, the daily solar fraction ranged from 0.33 to 0.41, and for the duration from August 2002 to November 2007 the total solar energy supplied to the chiller is 53914 kWh and the total external energy (gas energy) supplied to the chiller is 35249 kWh and their percentage are about 60% and 40%, respectively as shown in Figure (3).

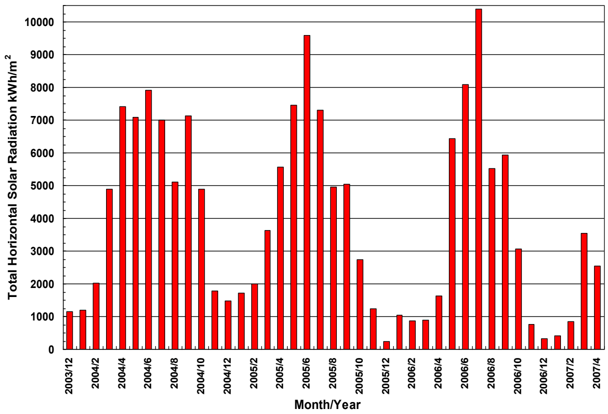


Fig. 2 The monthly total incident solar energy on the horizontal per meter square at the plant location

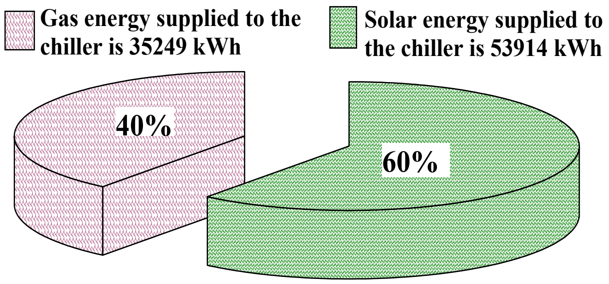


Fig. 3 Total solar energy supplied to the chiller and as well as the total external energy and their percentage for the duration from August 2002 to November 2007.

The instantaneous performance of the vacuum tube solar collectors' field is presented by the experimentally determined collector efficiency obtained from different measurements during clear sky days data, which exists few days a year, and are shown in Figure (4). The efficiency, η, characteristics are determined according to the ASHRAE Standard 93-77 cited in Duffie and Beckman [6]. which is plotted as a function of $(T_m - T_{amb})/I$. The presented data are corresponding to the values obtained 2 hours before and after noon (when the solar angle is nearly normal). In which T_m is mean average temperature of the water inside the collector and T_{amb} is the ambient air dry-bulb temperature. The results shown in Figure (4) have an instantaneous mean efficiency value of about 0.63. This value is within the range of the performance data of the manufacturer (61.1%, related to solar irradiation of 900 W/m² and T = 105/98/25 °C) as the present operating condition is slightly different. However, it's less than would be expected when compared with many vacuum tube collectors performance available in the market working at similar operating condition. Also, it is found that, the monthly average value of solar heat fraction varies from 31.1 % up to 100 %, with a five-year average value of 60 %. The main factors affecting the solar heat fraction are the meteorological conditions and the time of day when the plant is operated as both influence the level of incident solar insolation. In addition, the monthly average value of the collectors' field efficiency varies from 34.1 % up to 41.8 %, with a five-year average value of 28.3 % (not presented). These monthly and yearly average values of the collector efficiency can be enhanced by cleaning the collectors' tubes outer surface from the stick fouling once a year. This could be a further method to enhance the solar system efficiency.

4.2 Operational Characteristics of a Solar Powered Absorption Chiller

To clarify the effect of the daily cold energy demand on the chiller COP, accumulated results for 3 years of operation are shown in Figure (5). The data for the year 2004 with sample of daily operation condition is chosen as a case of the plant

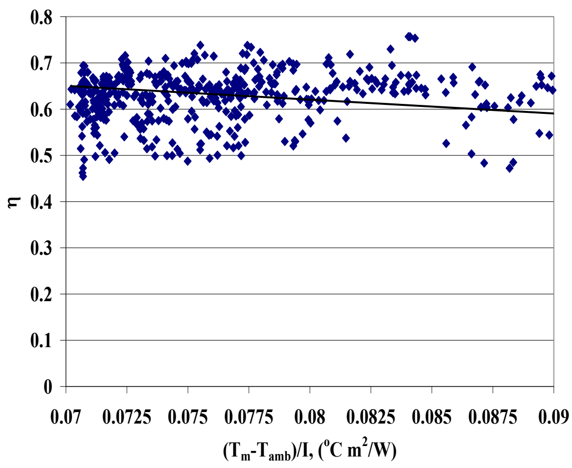


Fig. 4 Instantaneous collectors field efficiency

operation when the driving heat is only from solar energy source. The plant control system is set to give the priority of using free cooling over the chiller cold produced, when the free cooling is available. Therefore, the variations in COP values shown in Figure (5) are mainly attributed to the chiller operating conditions that differ from the rated conditions. From the plant data recorded, it is found that the daily average COP of the chiller decreases at lower cold demand is mainly due to a greater portion of the daily cold load demanded of the building is covered by the free cooling, while the chiller covers the rest of the load. From Figure (5), it can be seen that as the load cold demand is around 600 kWh/day in hot days, the average daily COP of the chiller is around 0.6-0.7, which is close to the chiller nominal value reported by the manufacture. Under such condition, and, with absence of the free cooling in the plant, the chiller is working with the supplied nominal COP values reported by the manufacture. An example of daily recorded of the plant heating; cooling loads during a cooling session is shown in Figure (6). In the presented cooling session, it's clear that the main motive energy during the summer months is provided by the auxiliary heating system, while the minor is from the solar collector filed. It is believed that, in case of such similar solar driven cooling plant that installed and operating in a hot arid areas the required motive energy will be almost covered by the solar collectors' field.

4.3 Gained Operational Experiences

- The results shown in Figure (4) shows the collector filed have an instantaneous mean efficiency value of about 0.63. This value is less than would be expected compared with many vacuum tube collectors performance available in the market and working at similar operating condition. This a small degradation in the performance is attributed, based on the visual inspection of the collectors' glass tube, to a thin stick fouling material combination of residual combustion gasses and other materials over the tube surfaces is observed.

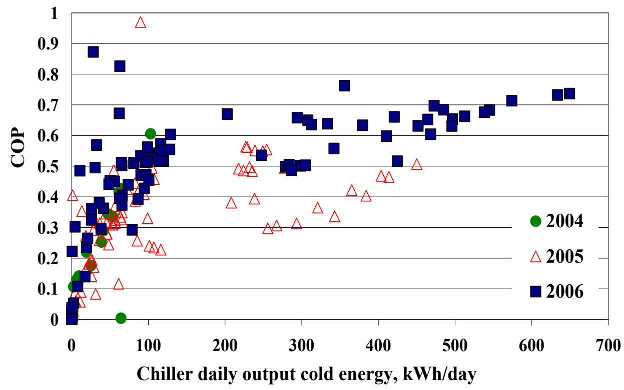


Fig. 5 Dependence of the chiller daily average coefficient of performance on the cold energy demand

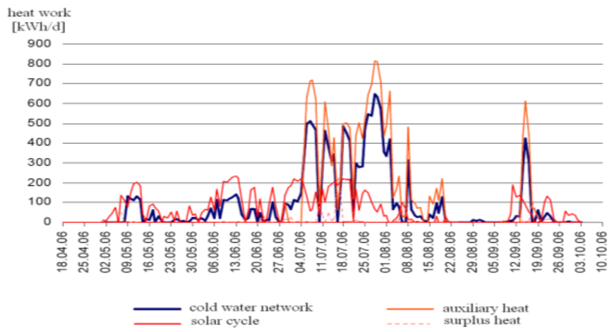


Fig. 6 Daily energy supply/consumption of the solar cooling plant

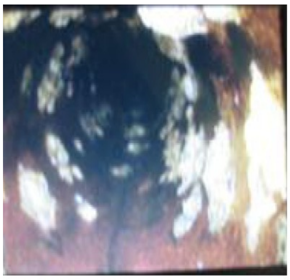
These fouling materials are not removable instead of heavy summer rains. This fouling acts as one reason for the decreases in collector field performance. Thus, periodical cleaning is required to keep the collectors' field working efficiently.

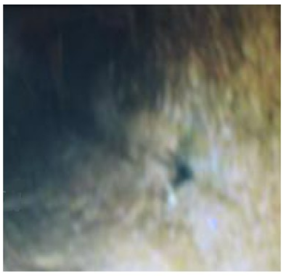
- The time span to reach a first capacity output from the chiller can be about 15 min. This time became longer, especially if the chiller has not been in operation for a longer time, e.g. within the transition time in spring and autumn or after wintertime. In these cases the driving hot water temperature (water entering the chiller's generator) should be close to 100 °C to overcome the crystallization occurred during shutdown period. Also, the temperature of water entering the chiller's generator should be continuously observed in order to ensure delivery of sufficient thermal energy to drive the internal thermosyphon pump effect within the generator and to avoid crystallization. In case the hot water supplied from the hot water storage tank drops below 78°C the backup heater is activated. In case of water entering temperature dropping below 75°C, the chiller is shutdown.

- In 2003 leaks in the re-cooling cycle were found. The reason of the leakages was corrosion of the welding seam of the steel pipes, although a re-cooling water treatment was run. A refurbishment of the re-cooling loop was carried out in the year 2004. The pipelines of the re-cooling cycle were pickled by hydrochloric acid to remove corrosion products, afterwards the pipelines were rinsed and existing leakages repaired. Figure 7 shows two photos of the inner wall of the pipelines before and after the treatment.

4.4 The Appropriate Small-Scale Solar- Driven Cooling Plant for Hot Arid Areas

The market potential for solar cooling systems with small-scale capacity is very large, so that different companies are developing solar cooling systems/kits for the product business. In the last 2 year (2008 and 2009), few companies in the solar business have positioned on the market as system providers for small scale solar cooling systems. The small-scale cooling capacity can reach up to 30kW. It is known that, the basic solar cooling systems contain solar thermal collectors with attachment, hot water storage, pump-sets, a chiller, re-cooler





before treatment after treatment

Fig. 7 Photos of the inner wall of the pipelines of the re-cooling cycle before and after treatment

(cooling tower), cold water storage and a control unit. Until now, almost all of these cooling kits in the market are developed for the European market which is based on the re-cooling is done by water and the heat rejected to the atmosphere achieved through a cooling tower. However, in hot arid areas, the water normally is rare, thus the re-cooling system should be built and designed based on dry re-cooling techniques.

In addition, the major problems facing solar sorption cooling systems are higher initial capital cost. One way of cutting costs may lie in the solar collectors, which are still expensive and burdensome for public use. Now in the market a small-scale, compact size adsorption chiller, with environment friendly refrigerant that can compete with vapor compression systems, is exist. Such small cooling capacity compact size chillers can be driven by hot water at 75°C that can be obtained from flat plate solar collectors' field. Thus, it is expected that an alternative choice, based on the total initial capital cost of the entire solar cooling system, is to select adsorption-cooling technology for small-scale solar-driven air-conditioning systems. This is because adsorption cooling system technology can be driven by a low temperature energy source that can be obtained from flat plate collectors. Based on the market price, costs are a bit lower for flat plate collectors with liquid heat transfer carrier. The average value of the specific collector surface for all unite installed until the year 2006 in Europe is about 3 m²/kW. A value from 3.5 to 4.5 m²/kW can be considered as a reference value for thermally driven absorption and adsorption chillers. However, these values are only rough reference values and can never replace the detailed design and simulation of a system. The specific cost of the whole installed solar cooling system in Europe is so far between 5,000 and 8,000 EUR/kW. In the year 2008, system prices goes down to 4,500 EUR/kW.

5. Conclusion

In this study, reporting the performance evaluation as well as the gained operational experiences of a solar driven cooling plant after 5 years in operation, in addition, based on the gained experiences, a suggestion for an appropriate small-scale solar-driven cooling plant for hot arid areas is presented. The plant includes a 35.17 KW cooling (10-RT) absorption chiller, vacuum tubes collectors with gross and net areas of 108 m^2 and 72 m^2, a hot water storage capacity of 6.8 m^3, a cold water storage capacity of 1.5 m^3 and a 134 kW cooling tower. The plant provides air-conditioning for a floor space of 270 m^2. The plant provides the air conditioning and chilled water demand for Fraunhofer Institute UMSICHT in Oberhausen-Germany since August 2002. From 2005 until now the plant has been additionally operating in connection to the institute heating system in order to use excess solar heat for heating purposes and to utilize the available hot water of the Institute heating system as a supplementary source in case the solar collector field supply heat is not enough to drive the chiller at cooling season. The main findings of the present study can be summarized as follows:

- The monthly average value of solar heat fraction varies from 31.1 % up to 100 % and the five years average value was about 60 %.
- The collectors' field instantaneous mean efficiency value was about 0.63, the monthly average value varied from 34.1 % up to 41.8 % and the five-year average value of 28.3 %.
- For sunny days with almost equal incident solar radiation and clear sky from clouds, the daily solar heat fraction ranged from 0.33 to 0.41, collectors' field efficiency ranged from 0.352 to 0.492 and chiller COP varied from 0.37 to 0.81, respectively.

The gained from the operational experiences are:

- In hot arid areas, the water normally is rare, thus the re-cooling system should be designed based on dry re-cooling techniques.
- Moreover, based on the total initial capital cost of the entire solar cooling system, adsorption-cooling technology for small-scale solar-driven air-conditioning systems is the most appropriate. This is because these chillers can be driven by a low temperature energy source that can be obtained from flat plate collectors where, costs are a bit lower for flat plate collectors with liquid heat transfer carrier.

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