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Experimental Study on Performance of Solar Thermal Driven Cooling System Versus a Hybrid Mechanical Compression Refrigeration-Solar Thermal Assisted System in Hot Areas

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Short Abstract

Refrigeration and air conditioning systems are essential requirements for human needs, and, this followed by an increasing demand for electric energy. The recent trend in research and development find such systems to be driven entirely or partiality by renewable energy. One goal of this study is to minimize the grid-based electrical power needed by the residential scale air conditioning system through either using full, driven or partiality solar thermal energy. The study main aim is to present the reduction in the electrical power consumption by the mechanical compression refrigeration system through integrating an intermediate solar thermal to raise the pressure of the refrigerant after the compressor and before the condenser and to compare this system performance with an entirely driven solar thermal cooling system under hot, arid areas.

This is being done through design, constructing and operation of both systems and carrying out the performance measurements under Assiut city environmental conditions.

Keywords: Residential scale solar cooling systems; solar thermal air-conditioning; Global warming assessments and Cost Competitiveness

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1. Introduction

The increased living standards accompanied with occupant thermal comfort demands leads to growing in the air-conditioning market worldwide in both commercial and residential sectors, followed by an increase in energy demand. Although the recent market available electrically driven conventional air-conditioning systems have reached a relatively high standard concerning energy consumption, however, they still require a significant amount of electricity that causes significant peak power loads on the grids in countries located in hot areas. This problem of growing energy demands is evident in the summer session of 2015, based on the number of electricity shortages cases created due to air-conditioning appliances. This rapid growth in the energy utilization sector with its impact on environmental awareness has led to more concern in the utilization of renewable energies driven cooling technologies in the last years with a focus on solar energy as an energy driven source. Solar energy cooling comprises attractive features as the incident solar insolation matches the cooling load profile within the buildings during the cooling season. The solar-driven cooling system consists of two main subsystems: solar energy conversion and storage system, and, the appropriate cooling production machine. Solar energy conversion and storage system are classified into two main groups depending on the form solar energy supply to the cooling device: thermal/work driven system and electricity (Photovoltaic-PV) driven system. Selection of a cooling machine type depends on temperature level of the cold demand as well as the possible environment for heat rejection from the system. Until a few years ago the focus was on using the solar thermal cooling in domestic buildings with more focus on the development of solar thermal driven technologies that can utilize the solar thermal energy to produce cooling. The study main aim is to present the reduction in the electrical power consumption by the mechanical compression refrigeration system through integrating an intermediate solar thermal to raise the pressure of the refrigerant after the compressor and before the *condenser* and to compare this system performance with an entirely driven solar thermal cooling system under hot, arid areas.

2. Methods

Solar Thermal Cooling System

The main components of the solar thermal driven adsorption cooling system supply the cooling demand for the renewable energy lab of 80 m2 floor area at the Faculty of Engineering, Assiut, Egypt (27.18oN Latitude and 31.19oE Longitude) is shown in figure (1). The system consists of the following main components: (1) evacuated tube solar collector field with an apparent area of 36 m2 modified with the back high reflective parabolic surface under the vacuum tubes. (2) Hot water storage (buffer) tank with a useful volume of 1.8 m3. (3) Adsorption chiller with 8 kW nominal cooling capacity (tow beds silica gel-water). (4) Cold water storage tank with a useful volume of 1.2 m3. (5) 34 kW or 50 kW capacities wet cooling tower for the chiller cooling process. (6) six energy-saving pumps. (7) Cooling load with two 4.5 kW capacity fan-coils. (8) The intermediate heat exchanger in chiller cooling subsystem, expansion tanks, backup gas water heater, controllers, measuring sensors and data acquisition system with impeded controller.

The solar thermal driven cooling system consists of six circuits, and the water is the heat transfer carrier in the system circuits. Each circuit has variable speed pump, water flow meter, and thermal expansion tank(s). The circuits are as follows: solar subsystem circuit that consists of the collectors' field and hot water storage tank, the chiller hot-water driving energy circuit, which consisted of the chiller, backup hot water gas heater, and the hot water storage tank. The chiller closed loop cooling water circuit that consists of the adsorption chiller condenser and adsorber and intermediate plate and frame heat exchanger, the open loop cooling water circuit, which consists of the cooling tower and intermediate plate and frame heat exchanger. The chiller chilled water circuit that consists of the adsorption chiller evaporator and the cold-water storage tank, the cooling load water circuit that consists of the cold-water storage tank and the fan-coils. The collectors' field is facing south direction, tilted by a 22-degree angle with the horizontal, and is arranged in two sub-fields each consist of three parallel arrays and each array includes a set of three collectors connected in series to provide the required driving heat at particular water temperature. The adsorption chiller that is shown in Figure (1) has two beds of silica-gel with a rated cooling capacity of 8 KW at a driving hot water temperature of 85 °C and cooling water temperature of 30 °C as reported by the manufacturer. This chiller can operate with hot water supply temperature ranges from 60°C to 95°C, and cooling water ranges from 27 °C to 32 °C. The cooling tower is shown in Figure (1) is installed on the rooftop of the heat laboratory and is selected based on the recommendation of chiller maker when using wet cooling tower with a capacity of 34 KW. This cooling tower as reported by manufacturer operates at 24 °C Air Wet Bulb (WB) temperature and 5oC range. In summer 2014, a higher cooling capacity tower of 50 kW replaced 34 kW tower in the system. The new cooling tower is designed to operate at a condition of 22°C air Wet Bulb (WB) temperature and 5oC temperature range based on the weather data in system site. The covered cooling load is for the Renewable Energy Laboratory that has a floor area of 80 m^2 and height of 3.55 m; six variable speed centrifugal pumps were used in the system six circuits as shown in figure (1). The chiller and load circuit pumps were controlled by the controller embedded in the logger.

Conventional Air Conditioning with solar thermal assisted System

The conventional electrically driven AC system with the solar thermal assisted system is the split type of 12000BTU/hr cooling capacity. The performance of this system is presented by the coefficient of performance (COP) as the ratio of the cooling capacity of the chiller (from the measurement of the air mass flow rate and the average temperature difference across the evaporator) and the input electrical power to the system.

Measurements, Data Reduction, and Experimental Error Analysis

The solar-driven cooling system was fully automated in operation by the embedded controller in the data logger through a computer interface. Also, the data logger with computer interface was used for system monitoring as well as the operating parameters measurements and data recording. In the system, all temperatures were measured at a particular location for monitoring, control, and performance analysis.

Temperatures were measured by temperature sensors type PT1000. The solar radiation flux measured at the collectors plan with same tilting angle by Pyranometer with an accuracy of ±0.5% within the measuring range from 0 to 2800 W/m2, and, 1 % from normalization from 0 to 70-degree zenith angle. A humidity sensor with the standard signal of 0-10 V correspondence to measuring range from 0 to 100% measured ambient air relative humidity (RH) with an accuracy of ± 2 % for the measured values between 30 and 90%. Water flow rate was measured by pulse meters, where six flow meters were used in the system having a measuring range as

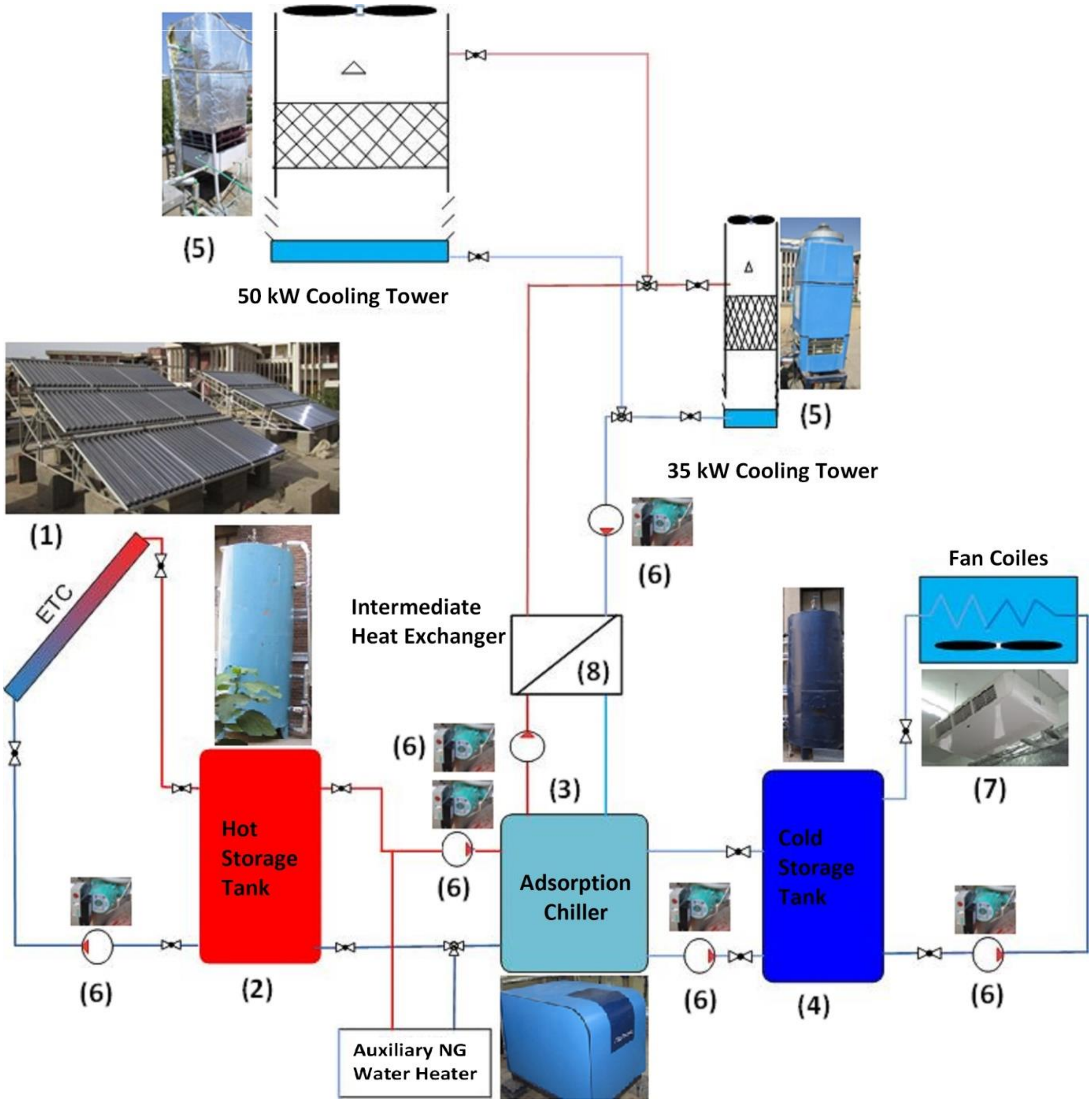


Figure 1 Hybrid schematic and photographs diagram of the main components of the solar cooling system: (1) collectors' field (2) hot water storage tank (3) adsorption chiller (4) cold water storage tank (5) cooling tower(s) (6) six-variable speed pumps (7) cooling load- fan coils and (8) intermediate heat exchanger.

follows: from 0 to 6 m3/h for the chiller cooling water and cooling tower circuits. While flow meters with a range from 0 to 2.5 m3/h are used in the solar collector's field circuit, the chiller is driving hot water circuit, chiller chilled water circuit and cooling load fan coils circuit. For system control purpose, pressure transducers having a measuring range from 0 to 6 bars measured the gauge pressure at several points in the system circuits.

Assessment of solar driven cooling system performance in operation under hot, arid climate requires determination of the chiller driving thermal power, the chilling chiller capacity, and collectors filed useful gained thermal power. The quantities of those parameters are determined as follows:

$$Q = \dot{m} \times C_p \times \Delta T \qquad (1)$$

Where:
Q= heat rate (kW)
ṁ= water mass flow rate (kg/s)
Cp= water specific heat (kJ/kg.ºC)
T= temperature difference (ºC)

The chiller coefficient of performance is determined by

$$COP = \frac{Q_{chw}}{Q_{input}} \qquad (2)$$

Where:
COP= chiller coefficient of performance
Qchw= chiller chilling capacity (kW)
Qinput= chiller driving power (kW)

The collectors' field overall efficiency is determined by

$$\eta = \frac{Q_{cll}}{G_T \times A_{cf}} \qquad (3)$$

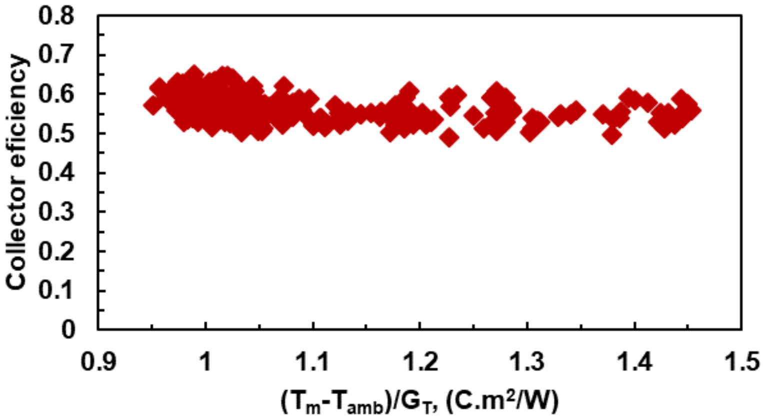
Where:
η= collector field overall efficiency
Qcll= collectors' field output thermal power (kW)
GT= total measured incident solar radiation flux on the collectors' field surface (kW/m2)
Acf= apparent total area of the solar collectors' field (m2)

In this study, the uncertainty in the determined quantities from the measured values and the instrumentation accuracy were calculated using the formulas of Coleman and Steele (1999). The uncertainty reported by the manufacturers' sheets of the instrumentation used to measure temperature, solar radiation, water mass flow rates were used in experimental error analysis. Throughout all experiments, the uncertainties in the presented values are as follows: in the temperature was 0.29%, heat transfer rates were 4.2%, COP was 4.8%, and collectors' efficiency was 2.6%.

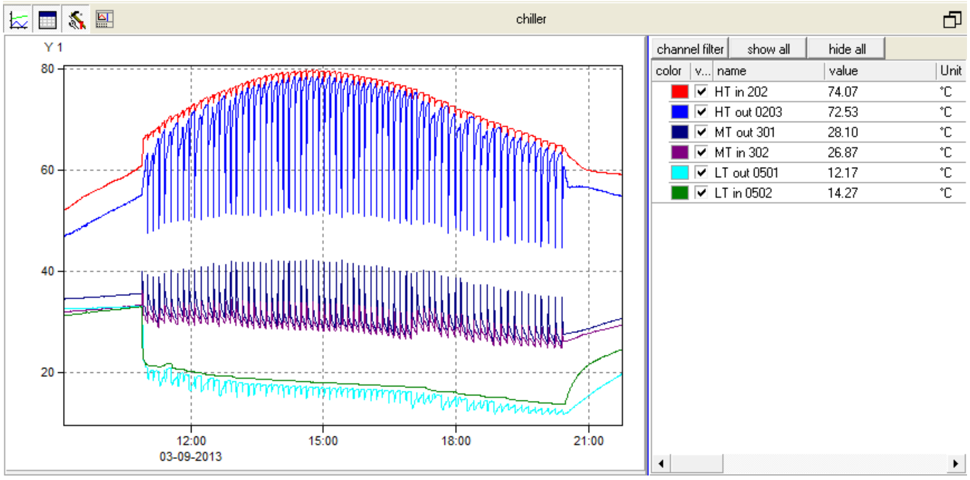
3. Results and discussion

Systems Performance

The solar thermal driven adsorption cooling system is in operation since summer 2012 until now. Therefore, a significant amount of data and results were obtained. However, the only sample of performance assessment results for a day during those years are presented and discussed. The performance of the system is expressed regarding the solar collector field efficiency, cooling tower outlet temperature, chilling chiller capacity, the temperature of chilled water outlet the chiller and the chiller coefficient of performance (COP). Figure (2-a) shows the instantaneous solar collector efficiency as a function of the average mean temperature of the water inside the collectors the collectors' field (Tm), the ambient air dry bulb temperature, and the incident solar radiation on the collector plane according to ASHRAE 93-77 Duffie and Beckman (2006). The presented data are corresponding to the measured values obtained for 2 hours before and after the noon. Clearly from figure (2-a) the collector efficiency ranged from 46.7 % to 66.4 % as the inlet water temperature ranged between 56.7 ˚C and 73 ˚C, and the outlet water temperature ranged from 67.7 ˚C to 83.5 ˚C, ambient air temperature ranged from 30 ˚C to 36 ˚C, the solar radiation flux was between 795 and 991 W/m2, respectively. The figure shows that the collectors' field efficiency was almost constant during the day. Such results are expected for vacuum tube collectors with a parabolic high reflective surface under the evacuated tubes in collectors. The daily solar collector efficiency during the reported period of system operation ranged from about 50 % to 78 %. Assessment of the sub-system components performance is carried out for a moderate weather day of September 3, 2103, and is presented in figure (2). The figure shows the operational characteristics of the adsorption chiller that obtained as a screen shot from the data logger software. Figure (2-b) shows a screen shot for the driving hot water temperature inlet and outlet from the chiller (HT), chiller cooling water temperature inlet and outlet from the chiller (MT) and cold-water temperature outlet and inlet to the chiller. While figure (3-c) shows a screen shot of the chiller driving thermal power, chilling power and heat rejected power (CW power). Clearly, the results illustrated in figure (2-b and c) indicate that the chilled water outlet temperature from the chiller is 20.6 ˚C and decreases with time until reach to 12.2 ˚C, while the chiller cooling water temperature was decreased from 31.4˚C at the start and became 26.9 ˚C at the end of this day experiment. The chiller driving hot water temperature was 65 ˚C at the beginning of the experiment and reaches to 80.4˚C around noon, and, then decreased again. For that day, the total driving heat energy supplied to the chiller was about 310 MJ; the solar energy obtained from the collectors' field was about 439.5 MJ. In that day the collector field average efficiency was 0.5 and the chiller produced about 136.1 MJ cold energy with daily chiller COP of 0.44. For the chiller working hours, the average chilling power was about 3.6 kW, which presents about 45% of the rated chiller nominal capacity. These results mainly attributed to the higher inlet cooling water temperature to the chiller to cool both the adsorber and condenser. For example, the overall performance results of the cooling session for summer of 2012 are summarized as follows. The chiller average daily COP was 0.41 with the average chilling power of 4.4 kW at the cooling water outlet temperature from the cooling tower of 31˚C, and the outlet chilled water temperature was about 19˚C, correspondence to average outdoor Ambient Dry Bulb temperature of about 40oC and Wet Bulb temperature of about of 21°C. Therefore, based on cooling tower outlet water temperature of 31oC city water at a temperature of 27.5˚C was used as a cooling medium instead of



(a)



color	v...	name	value	Unit
🟥	☑	HT in 202	74.07	°C
🟦	☑	HT out 0203	72.53	°C
🟦	☑	MT out 301	28.10	°C
🟪	☑	MT in 302	26.87	°C
🟦	☑	LT out 0501	12.17	°C
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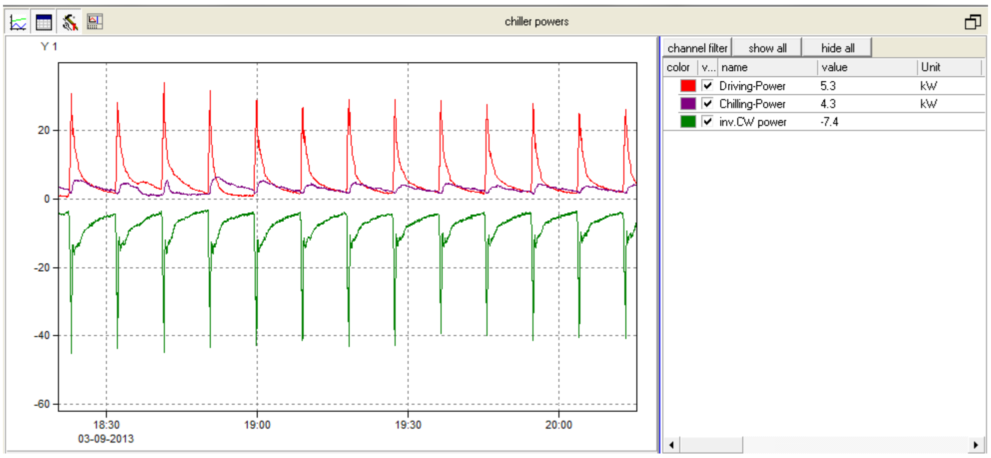
(b)



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🟥	☑	Driving-Power	5.3	kW
🟪	☑	Chilling-Power	4.3	kW
🟩	☑	inv.CW power	-7.4	

(c)

Figure 3 Sub-system components performance is on September 3, 2103 (a) solar collectors' field efficiency, (b) screenshot from the data logger for driving hot water temperature inlet and outlet from the chiller (HT), chiller cooling water temperature inlet and outlet from the chiller (MT) and chilled water temperature outlet and inlet to the chiller and (c) screenshot from the data logger for the chiller driving thermal power, chilling power and heat rejected power (CW power)

4. Conclusions

In this study, performance evaluation of two residential scales entirely or partially driven solar thermal air-conditioning in hot, arid areas is carried out throughout an applied research project in which two cooling systems were designed, build and operated at Assiut, Egypt

The experimental results for both systems show that the indoor thermal comfort conditions are achieved in the hottest days of the year.

The results clearly indicate that: Compared with the conventional vapor AC driven air-conditioning system with partially driven solar thermal, the solar thermal driven cooling system has an energy consumption of 10.94%, with Total Equivalent Warming Impact (TEWI) of 9.96% and total cost per kW cooling is 295.96%.

5. References

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