Journal of Applied Mechanical Engineering
ISSN: 2168-9873

Begum et al., J Appl Mech Eng 2018, 7:4
DOI: 10.4172/2168-9873.1000310

Research Article Open Access

Effect of Flow Rate on Performance of Solar Adsorption Chiller Keeping Fixed Evaporator Outlet Temperature

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Abstract

A two bed basic adsorption chiller run by solar heat is investigated to get a fixed chilled water outlet temperature. Generally, a solar heat driven adsorption chiller, being activated with intermittent heat source, cannot produce uniform cooling. In this context, it is found that the flow rate of inlet chilled water can help to keep the evaporator outlet temperature constant. The performance of the chiller is also observed at day time for the climate condition of Dhaka, Bangladesh. Silica gel and water is considered as the working pair in the present study. The results show that 1100sec cycle time along with 38.64m2 collector area gives better performance with fixed chilled water outlet temperature (7°C).

Keywords: Adsorption chiller; Refrigerant; Solar heat; Air conditioning; Green energy

Abbreviations:*A*: Area; C: Specific heat; Dso: Diffusion coefficient; Ea: Activation energy;*I* : Solar radiation; *L*: Latent heat of vaporization; *m*: Mass flow rate; $Q_{st:}$ Heat of adsorption; Pr: Prandle number; *q*: Adsorption capacity; Re: Reynold number; $R_{gas:}$ Water gas constant; $R_{p:}$ Silica gel particle diameter; *T*: Temperature; $\bar{t}$: Time; W: Mass; am: Ambient; bed: Adsorbent bed; chill: Chilled water; cool: Cool water; Con: Condenser; eva: Evaporator; f: Heat transfer fluid (water); hot: Hot water; in: Inlet; l: Liquid; M: Metal; out: Outlet; r: Refrigerant; s: Silica gel/saturation; δ: Logical parameter; η: Collector efficiency; λ: Thermal conductivity; μ: Viscosity.

Introduction

Energy consumption is increasing around the world. Cooling is one of the reasons of increasing energy demand. To meet the demand in cooling, mechanical vapor-compressor commonly used which can be classified as conventional systems [1]. These systems are very popular due to their high coefficient of performance, small sizes and low weights. They also exhibit some disadvantages such as contributing to global warming and ozone layer depletion and high energy consumptions. This research is focused on one of the sustainable ways to decrease energy demand for cooling one of which could be the solar-powered adsorption cooling system. The advantage and development of adsorption cycle is widely studied by Meunier [2]. At the same time Wang et al. [3] studied the performance of adsorption based refrigerator with a single bed. Different sorption systems were compared thermodynamically by Pons et al. [4] in terms of coefficient of performance (COP) using different working pairs. A new design for two-stage adsorption cooling systems with two adsorbent beds was analyzed by Saha et al. [5]. The dynamic performance of a continuous adsorption cycle using a double adsorber along with heat recovery is measured in terms of the temperature histories, gross solar coefficient of performance and specific cooling power by Yong et al. [6]. A two-stage adsorption refrigeration chiller using re-heat to determine the influence of the overall thermal conductance of sorption elements and evaporator as well as the adsorbent mass on the chiller performance was investigated by Khan et al. [7]. A simple adsorption cooling cycle was also developed by Chang et al. [8] using a silica gel-water pair. Alam et al. [9] investigated the performance of two-bed conventional adsorption cooling cycle driven by solar heat where CPC solar panel is used under the climatic condition of Tokyo. The maximum COP_{cycle} and COP_{solar} recorded as 0.55 and 0.3 respectively, with solar radiation 963.89 W/m^2 for the month of August in Tokyo. A lumped parameter model of a silica gel–water adsorption chiller driven by solar energy was introduced for the operating characteristics investigation by Zhang et al. [10]. Saha et al. [11], Boelman et al. [12] and Chua et al. [13,14] studied adsorption refrigeration cycle using the silica gel–water pair which can be driven by 80°C heat source temperature with 30°C cooling source. Saha et al. [15] studied a three-stage adsorption chiller to get better performance. Alam et al. [16] added a tank with the chiller to get benefit till late night under the climatic condition of Dhaka.

As a tropical country, Bangladesh has the prospect to utilize solar energy as a driving source for adsorption refrigeration and air conditioning system. Fixed temperature is an important issue to preserve medicine and food at remote area. For this reason, in this study a single stage adsorption system which utilizes solar heat source to get a fixed average outlet temperature (7°C) during the day time. Various numbers of collectors (each of area 2.415 m^2) and cycle times have been studied to demonstrate the performance. Here it has also discussed about the variation of chilled water mass flow rate of fluid flow during the daytime to get a fixed average outlet temperature.

Working Principle

An adsorption chiller consisting of two adsorbent beds, one condenser and one evaporator as shown in Figure 1a has been considered in this research. Silica gel-water pair has been chosen as adsorbent/ adsorbate. There are four thermodynamic steps in the cycle, they are:

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Received May 23, 2018; **Accepted** August 08, 2018; **Published** August 10, 2018

Citation: Begum FA, Khan MZI, Rouf RA, Alam KCA (2018) Effect of Flow Rate on Performance of Solar Adsorption Chiller Keeping Fixed Evaporator Outlet Temperature. J Appl Mech Eng 7: 310. doi:10.4172/2168-9873.1000310

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- Desorption/ Condensation,
- Pre-Cooling,
- Adsorption/Evaporation
- Pre-Heating Process.

In the present study, no heat recovery or mass recovery process is considered. The adsorber (B1/B2) is alternately connected to the solar collector to heat up the bed during pre-heating, desorption/ condensation process and to the cooling tower to cool down the bed during pre-cooling, adsorption/ evaporation process. The heat transfer fluid transport heat from the solar collector to the desorber and returns the collector to regain heat from the collector. The valve between adsorber and evaporator and the valve between desorber and condenser are closed during pre-cooling/ pre-heating period while, these are open during adsorption/ evaporation and desorption/ condensation process.

The chiller has four modes, mode A, B, C and D (Figure 2). In mode A, B1-condenser is in desorption/condensation process and B2-evaporator is in the adsorption/evaporation.

In the desorption-condensation process, the desorber (B1) is heated up to desorption temperature by heat Q_{des}, provided by the driving heat source. The resulting refrigerant is cooled down by temperature (T_{con}) in the condenser by the cooling water, which removes heat, Q_{cond}. In the adsorption-evaporation process, refrigerant (water) in evaporator is evaporates in evaporation temperature and seized heat, Q_{eva}, from the chilled water. The evaporated vapour is adsorbed by adsorbent (silica gel), at which cooling water removes the adsorption heat, Q_{ad}. Mode B is switching process for B1 and B2. In this mode, B2 is heated up by hot water and B1 is cooled down by cooling water. In mode C, B1 works as adsorber and B2 works as desorber. Mode D is the next switching process for B1 and B2. After this mode, the system returns to mode A. The schematic of the adsorption cooling with solar collector panel is presented in Figure 1b.

Mathematical Equations

The components in detail and the related equations used in the model are presented here. It is assumed that the temperature, pressure and concentration throughout the adsorbent bed are uniform. The energy balance equation for the adsorption/desorption bed is given below:

$$\frac{d}{dt}\left\{\left(W_M C_{pM} + W_s C_s + W_s q C_{r,v}\right) T_{bed}\right\} = Q_{st} \cdot W_s \frac{dq}{dt} + \delta \cdot W_s C_{r,v} \frac{dq}{dt}\left(T_{eva} - T_{bed}\right) + \dot{m}_f C_f \left(T_{bed,in} - T_{bed,out}\right) \quad (1)$$

where, δ is either zero or one depending whether adsorbent bed is working as desorber or adsorber.

The energy balance equation for condenser can be stated through the following equation:

$$\frac{d}{dt}\left\{\left(W_{con,M} C_{con,M} + W_{con,r} C_{r,l}\right) T_{con}\right\} = -L \cdot W_{con} \frac{dq_d}{dt} + W_s C_{r,v} \frac{dq_d}{dt}\left(T_{con} - T_{bed}\right) + \dot{m}_{f,con} C_f \left(T_{con,in} - T_{con,out}\right) \quad (2)$$

The energy balance of evaporator can be demonstrated by the following equation:

$$\frac{d}{dt}\left\{\left(W_{eva,M} C_{eva,M} + W_{eva,r} C_{r,l}\right) T_{eva}\right\} = -L \cdot W_s \frac{dq_a}{dt} + W_s C_{r,l} \frac{dq_d}{dt}\left(T_{eva} - T_{con}\right) + \dot{m}_{f,chill} C_f \left(T_{chill,in} - T_{chill,out}\right) \quad (3)$$

The following equation is used to calculate the outlet temperature of the different water loops:

$$T_{out} = T + (T_{in} - T).\exp(-UA / \dot{m} C_f) \quad (4)$$

The cyclic average cooling capacity (CACC) can be evaluated by the following expression:

$$\text{CACC} = \frac{\int_{begin\ of\ cycle\ time}^{end\ of\ cycle\ time} \dot{m}_{chill} C_{chill,f} (T_{chill,in} - T_{chill,out}) dt}{Cycle\ time} \quad (5)$$

The cycle COP (Coefficient of performances) can be calculated by the following equation:

$$\text{COP}_{cycle} = \frac{\int_{begin\ of\ cycle\ time}^{end\ of\ cycle\ time} \dot{m}_{chill} C_{chill,f} (T_{chill,in} - T_{chill,out}) dt}{\int_{begin\ of\ cycle\ time}^{end\ of\ cycle\ time} \dot{m}_f C_f (T_{d,in} - T_{d,out}) dt} \quad (6)$$

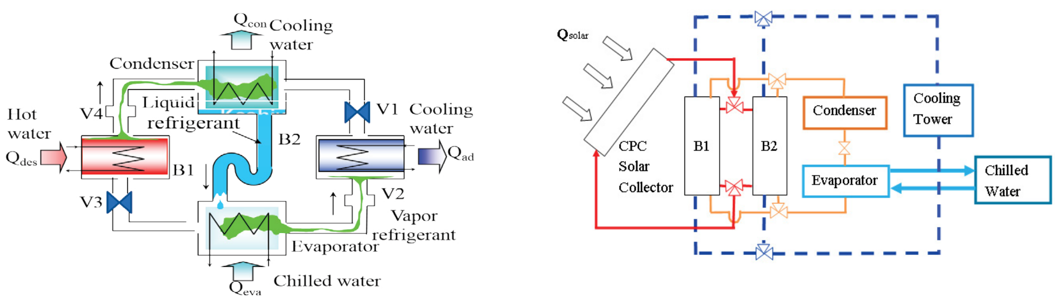
The heat source consists in ten enhanced compound parabolic concentrator (CPC) developed by Solarfocus-GmbH with a total gross area of 24.2 m^2. An increase of 20% in efficiency is claimed by the manufacturer for these new CPCs compared to classical ones. In the present study, the same collector is used as used by Clausse et al. [17]. The parameters used in the calculations are shown in Table 1.

Solar COP in a cycle (COP_{sc}) can be expressed as the following expression:

$$\text{COP}_{sc} = \frac{\int_{begin\ of\ cycle\ time}^{end\ of\ cycle\ time} \dot{m}_{chill} C_{chill,f} (T_{chill,in} - T_{chill,out}) dt}{\int_{begin\ of\ cycle\ time}^{end\ of\ cycle\ time} n \cdot A_{cr} I\, dt} \quad (7)$$

where, I is the solar irradiance, A_{cr} is each collector area and n is the number of collector.

For the present study, results are generated based on solar data of Dhaka (Latitude 23°46′ N, Longitude 90°23′ E) on April, chiller data and the collector data are same as Alam et al. [9]. In April at Dhaka sunrise time is taken as 5.5 h and sunset 18.5 h, while minimum and



(a) (b)

Figure 1: (a) Schematic diagram of a single stage adsorption chiller, **(b)** Schematic diagram of the solar driven adsorption cooling system.

Parameters	Value	Parameters	Value
A_{bed}	2.46 m²	Q_{st}	2.8E+06 J/kg
A_{con}	3.73 W/m².K	R_{gas}	4.62E+02 J/kg.K
A_{cr}	2.415 m²	R_p	0.17E-03 m
A_{eva}	1.91 m²	T_{cool}	30°C
$C_{r,l}$	4.18E+03 J/kg.K	T_{chill}	14°C
$C_{r,v}$	1.89E+03 J/kg.K	U_{bed}	1724.14 W/m².K
C_{cu}	386 J/kg.K	U_{con}	4115.23 W/m².K
C_{al}	905 J/kg.K	U_{eva}	2557.54 W/m².K
C_s	924 J/kg.K	$W_{con,M}$	24.28 kg
D_{S0}	2.54E-04 m²/sec	$W_{con,r}$	0.0 kg
E_a	2.33E+06 J/kg	$W_{eva,M}$	12.45 kg
L	2.5E+06 J/kg	$W_{eva,r}$	50 kg
$\dot{m}_{f,hot}$	1.3 kg/sec	W_{cp}	0.4913 kg
$\dot{m}_{f,cool}$	1.3 kg/sec	W_{fm}	64.04 kg
$\dot{m}_{f,cont}$	1.3 kg/sec	W_s	47 kg
N_p	9	W_{tm}	51.2 kg

Table 1: Parameters used in the simulation.

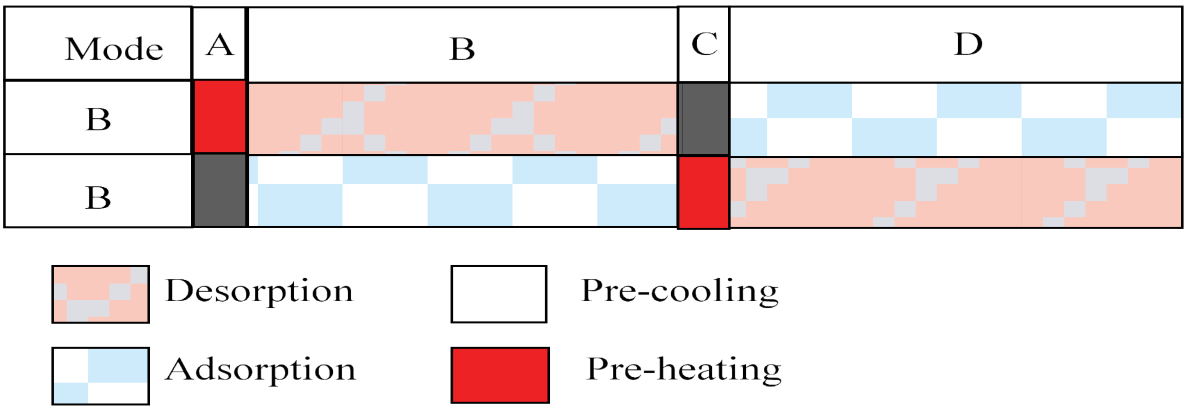


Figure 2: Operational strategy of the chiller.

maximum temperature for that month is 24°C and 34°C respectively. The maximum solar radiation in Dhaka for the month of April is taken as 771 W/m². This data is supported by RERC, University of Dhaka. The input data are furnished in Table 1.

The equations of desorber and collector are completely dependent on each other. Therefore, these equations are discretized by finite difference approximation method which forms a set of linear equations in terms of temperature and their outlets. Gaussian elimination method is exploited to solve the system of linear equations. The initial temperature, concentration and pressure are set based on the temperature of the beginning of the day, then the program is allowed to run consecutive few days unless the steady conditions arrive, that is, all the conditions at end of the day are same as beginning of the previous day. All results are presented here for the 3rd day on which program reaches its steady state condition so that all results are same for next consecutive days. The tolerance for all the convergence criteria is 10^{-4}.

Result and Discussion

Keeping average chilled water outlet temperature fixed at 7°C, the chilled water inlet flow rate effect on 38.64 m² collector area (16 collectors) with cycle time 1100 sec and 43.47 m² collector area (18 collectors) with cycle time 1000 sec is depicted at Figure 3a. For this study, the chilled water flow rate is taken as the variable parameter to keep the chilled water outlet temperature fixed at 7°C. It is observed that the chilled water flow rate increases as the driving heat source temperature increases. This happens because of refrigerant (water) in the evaporator is evaporated at an evaporation temperature seizing heat from the chilled water. It is seen that the maximum chilled water flow rate is 0.28 kg/sec for cycle time 1100 sec with 38.64 m² collector area and 0.3 kg/sec for cycle time 1000 sec with 43.47 m² collector area which occurs at 12:00 noon. The chilled water outlet temperature for different cycle time with different collector areas are shown in Figure 3b.

The collector outlet temperature profile for 38.64 m² collector area with cycle time 1100 sec and 43.47 m² collector areas with cycle time 1000 sec have been presented in Figure 4. It is observed that the collector outlet temperature reaches near 94°C when 43.47 m² collector area along with 1000 sec cycle time and near 92°C when 38.64 m² collector areas with 1100 sec cycle time considered. It is also seen that lower the collector area lower the driving heat source temperature.

The cyclic average cooling capacity (CACC) with same collector area and same cycle time has been shown in Figure 5. It is seen that cooling capacity is low at the beginning of the day and it increases until the maximum solar radiation obtained and after that it decreases again. It is also seen that as the collector area increases bed temperature also increases, therefore better adsorption/desorption appear, as a result better cooling production found. CACC are 8.9 kW and 8.1 kW at noon when 38.64 m² collector area and 43.47 m² collector areas are in use respectively.

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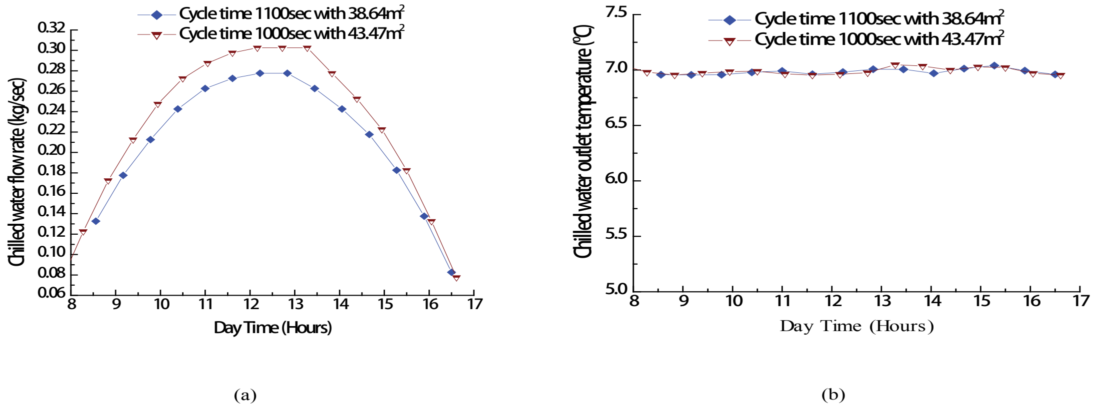

Figure 3: (a) Chilled water inlet flow rate, **(b)** Chilled water outlet temperature.

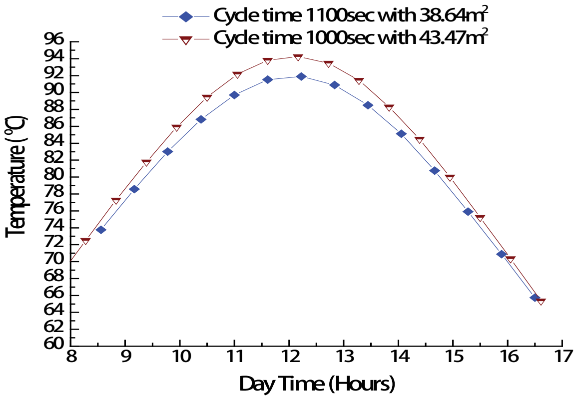

Figure 4: Temperature profile of collector outlet for different cycle time with different collector area.

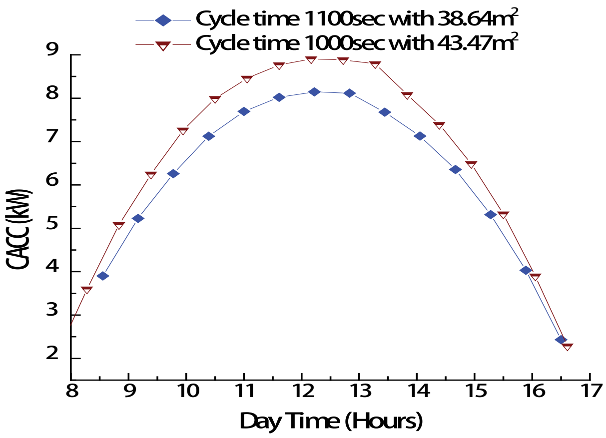

Figure 5: Cyclic average cooling capacity of the chiller for different collector area with different cyclic time.

The COP_{cycle}, $COP_{solar,cycle}$ and $COP_{solar,net}$ have been shown in Figure 6 respectively. It is seen that COP_{cycle} reaches around 0.5 while $COP_{solar,cycle}$ and $COP_{solar,net}$ reaches around 0.27 and 0.23 respectively for 38.64 m^2 collector area with 1100 sec cycle time and those are 0.49, 0.27 and 0.22 respectively for 43.47 m^2 collector area with 1000 sec cycle time. It indicates that with longer cycle time chiller gets better COP values. It is also seen that for both cases the maximum value of $COP_{solar,net}$ continue up to late afternoon. This is due to the effect of inertia of heat exchangers and adsorbent materials.

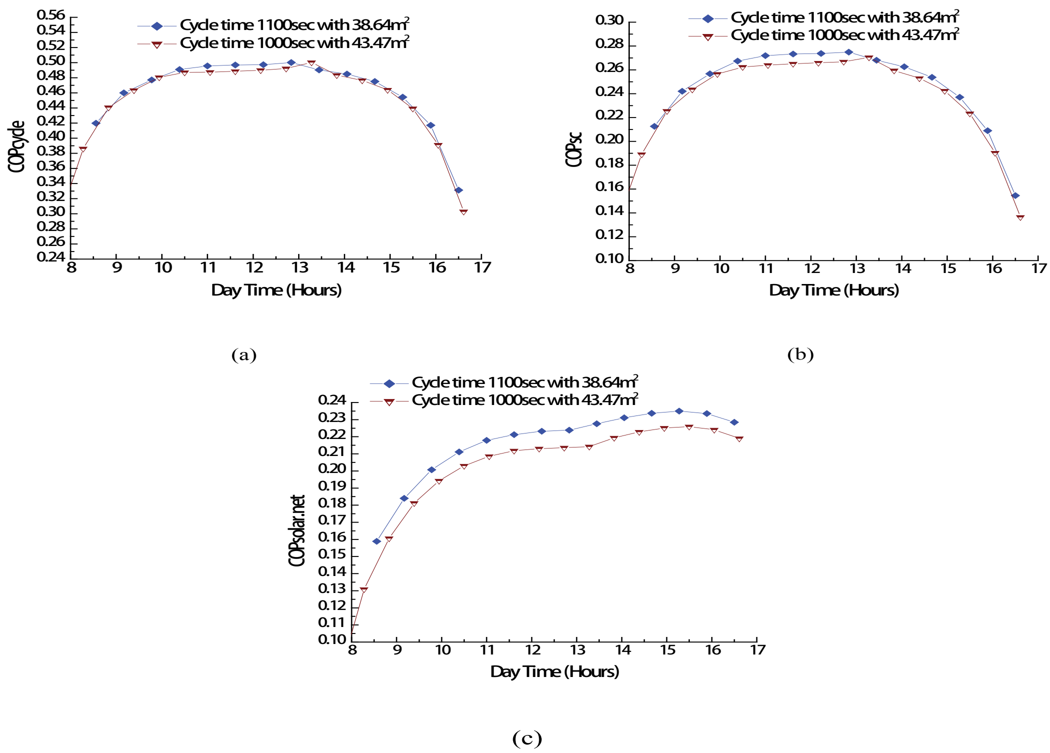

Figure 6: Performance of the chiller for different collector area with different cycle time (a) Coefficient of performance of cycle, COP_{cycle}, (b) Coefficient of performance of solar cycle, $COP_{solar,cycle}$ and (c) Coefficient of performance of net solar, $COP_{solar.net.}$

Conclusions

The present study has been investigated to maintain a fixed chilled water outlet temperature at 7°C. In this case 38.64 m^2 and 43.47 m^2 collector area has been considered with a two bed conventional single stage chiller. Here, silica gel and water has been utilized as adsorbent and adsorbate pair. According to the investigation, following claims can be made:

- The chilled water flow rate is an influential parameter for an adsorption cooling system run by solar collector and chilled water in flow rate need to be increased, as the solar radiation increases, to keep a fixed 7°C chilled water out flow.
- Cyclic average cooling capacity is around 8.1 kW for 38.64 m^2 collector area with 1100 sec cycle time at 12:00 noon with the collector outlet temperature of 92°C.
- Maximum value of COP_{cyle} is 0.5 and maximum value of $COP_{solar,cycle}$ and $COP_{solar,net}$ is 0.26 and 0.23 respectively with same set of collectors and cycle time.

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