# Simulation Study of Continuous Solar Adsorption Refrigeration System Driven by Compound Parabolic Concentrator

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**Abstract:** Solar adsorption refrigeration is promising technology especially in the developing countries and remote areas because the system can be driven by solar energy without involving electricity. Therefore, it is technologically possible and socially feasible in the areas where electricity is not enough but solar energy is rather easy to obtain. The conventional system works intermittently and produces cooling only during night. In this article, a solar adsorption refrigerator is presented that produces cooling continuously using only solar energy. The system consists of two beds with CPC collectors, a condenser and evaporator. The one cycle complete in two days. A simulation model was developed to evaluate the system performance. The objectives of this study were to investigate the dynamic behaviour of the system, and to compare the system behaviour with the conventional system. The results show that system produces continuous cooling. Cooling rate decreased in the middle of the day because of relatively high ambient temperature. The performance of the system increased with high value of heat transfer coefficient between receiver and bed, and decreased by increasing the adsorbent mass. The performance of the continuous system was compared with that of intermittent system. It was found that the evaporator temperature in the intermittent system increased during the day because cooling is not produced during day in that system, while proposed system kept the evaporator at low temperature continuously. This study will facilitate the future researches in solar adsorption continuous refrigeration technology because achieving continuous cooling only with solar energy is very attractive.

**Keywords:** Adsorbent bed, adsorption refrigeration, CPC, solar cooling, solar adsorption.

## 1. INTRODUCTION

The technology advancement has changed the life style in the remote areas especially rural areas in the developing countries. The cooling demand is also increased for various purposes, such as storing foods and medicines, cold water for drinking, and for space cooling. Normally, electric driven systems are used for refrigeration or cooling purposes. But the energy shortfall and insufficient electric supply are the main constrains to use the electric driven cooling system in remote areas. Therefore, it is needed to produce cooling from renewable energy resources that are naturally available and environmental friendly. Many researches have been conducted to use the renewable energy resources for refrigeration purposes. Solar cooling can be promising and attractive technique in future because of near coincidence of peak cooling loads with the available solar power. There are many solar cooling techniques such as absorption, adsorption, desiccant, and ejector system. Solar adsorption refrigeration has advantages over other systems because it can bedriven with low heat [1] and does not require electric power. These systems are easy operated without high skills and required less maintenance, moreover, the working pairs used in the systems are environmentally friendly [2]. On the other hand there are some remote areas, especially local areas in developing countries where electricity is not enough but solar energy is rather easy to obtain. From this point of view, it can be said that solar driven adsorption refrigeration is technologically possible and socially feasible in such areas.

Despite the potential advantages, the solar adsorption refrigeration technology is not competent to replace the electric driven refrigerator because of low efficiency, intermittency, and high initial cost. A number of researches has been conducted to improve the performance of conventional one bed solar adsorption refrigeration system by increasing the heat and mass transfer capability of adsorbent bed using fins [3, 4], adding metal pieces into adsorbent bed [5], using high conductive adsorbent [6] and consolidated bed [7]. In most of the studies, flat plate collectors were used [3, 4] and some attempts were also carried out by using concentrator collectors [8] especially compound parabolic concentrator (CPC) [9].

The conventional system worked intermittently, it collects solar energy in the day time and produce cooling at night, because there is only one bed that acts as desorber in the day and adsorber in the night. Various studies have been conducted to produce continuous cooling with multi bed and advance cycle operation in adsorption cooling system technology. The performance of these systems were enhanced by using the advanced operations like internal mass recovery cycle [10, 11], heat and mass recovery cycles [12], multistage and cascade

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**Table 1. Numerical values used in simulations.**

| Symbol | Value | Unit | Symbol | Value | Unit |
|---|---|---|---|---|---|
| **Adsorption Isotherm** | | | **Adsorbent Beds** | | |
| $W_o$ | 0.707 | kg kg$^{-1}$ | $M_{ACF}$ | changing | kg |
| $D$ | $1.716 \times 10^{-6}$ | K$^{-2}$ | $Cp_{ACF}$ | 941 | J kg$^{-1}$ K$^{-1}$ |
| **CPC Characteristics** | | | $Cp_{re}$ | 2400 | J kg$^{-1}$ K$^{-1}$ |
| $A_{ap}$ | 0.25/per CPC | m$^2$ | $\Delta H_{st}$ | $1.2\times10^6$ | J kg$^{-1}$ |
| $A_r$ | 0.098 | m$^2$ | **Condenser** | | |
| $L_{cpc}$ | 2/per CPC | m | $M_c$ | 2 | kg |
| $nr$ | 0.68 | - | $A_c$ | 0.4 | m$^2$ |
| $\rho_{cpc}$ | 0.92 | - | $h_{cc}$ | 15 | W m$^{-2}$ K$^{-1}$ |
| $\tau_{cpc}$ | $(\rho_{cpc})^{nr}$ | - | $L_{H,re}$ | $8.46\times10^5$ | J kg$^{-1}$ |
| **Cover** | | | **Refrigerator** | | |
| $M_{cov}$ | 0.9 | kg | $M_e$ | 4 | kg |
| $Cp_{cov}$ | 840 | J kg$^{-1}$ | $A_e$ | 0.86 | m$^2$ |
| $A_{cov}$ | 0.372/per CPC | m$^2$ | $A_{wt}$ | 0.37 | m$^2$ |
| $\alpha_{cov}$ | 0.05 | - | $U_e$ | 0.6 | W m$^{-2}$ K$^{-1}$ |
| $\tau_{cov}$ | 0.89 | - | $U_w$ | 5 | W m$^{-2}$ K$^{-1}$ |
| **Receiver** | | | $U_\beta$ | 0.2 | W m$^{-2}$ K$^{-1}$ |
| $M_r$ | 5 | kg | $L_{H,,w}$ | $2.5\times10^6$ | J kg$^{-1}$ |
| $Cp_{Cu}$ | 386 | J kg$^{-1}$ K$^{-1}$ | $Cp_{,w}$ | 4200 | J kg$^{-1}$ K$^{-1}$ |
| $U_{bed}$ | changing | W m$^{-2}$ K$^{-1}$ | - | - | - |
| $A_r$ | 0.95 | - | - | - | - |
| $\rho_r$ | 0.15 | - | - | - | - |

$\lambda$ is 1 when evaporator temperature is 0 °C or below otherwise it is 0.

### *Mass Balance of Refigerant*

$$\frac{dM_{ree}}{dt} = -M_{ACF}\left(\frac{dq^a}{dt} + \frac{dq^a}{dt}\right) \tag{11}$$

### *Performance Index*

The performance of the system is evaluated with specific cooling effect (SCE) and coeffcient of performance (COP) that are calculated as;

$$SCE = \frac{Q_e}{M_{ACF},total} \tag{12a}$$

where $Q_e$ is the cooling energy achieved by the evaporator and calculated by multiplying the total amount of adsorbed refrigerant with the latent heat of refrigerant;

$$Q_e = M_{adsorb} \times L_{H,re} \tag{12b}$$

and

$$M_{adsorb} = M_{ACF}(q_{max} - q_{min}) \tag{12c}$$

$$COP = \frac{Qe}{Aap\int_{end\ of\ desorption}^{sunrise}(I_{bm}cos\theta_i + I_{diff})(t)\,dt} \tag{13}$$

The supplementary equations to calculate the $h_{Rr}$, $h_{Rs}$, $h_{rc}$ and $h_{ca}$ used in the mathematical models are given in reference [16, 21]. The numerical values used in the simulation are given in Table **1**.

### *Initial Conditions*

$$T_{cov}(0) = T_r(0) = T_{bed}(0) = T_c(0) = T_{air} \tag{14}$$

and,

$$T_e(0) = T_w(0) = 285\ K \tag{15}$$

### Boundary and Operating Conditions

The actual measured data for solar radiation, ambient temperature and wind velocity was used in the simulation for

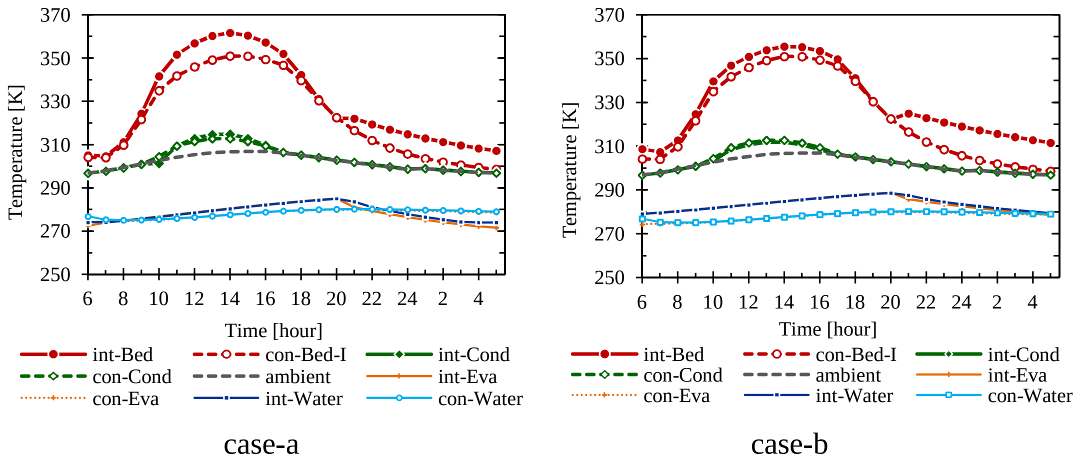


**Fig. (10).** Comparison between system temperature of intermittent and present continuous system.

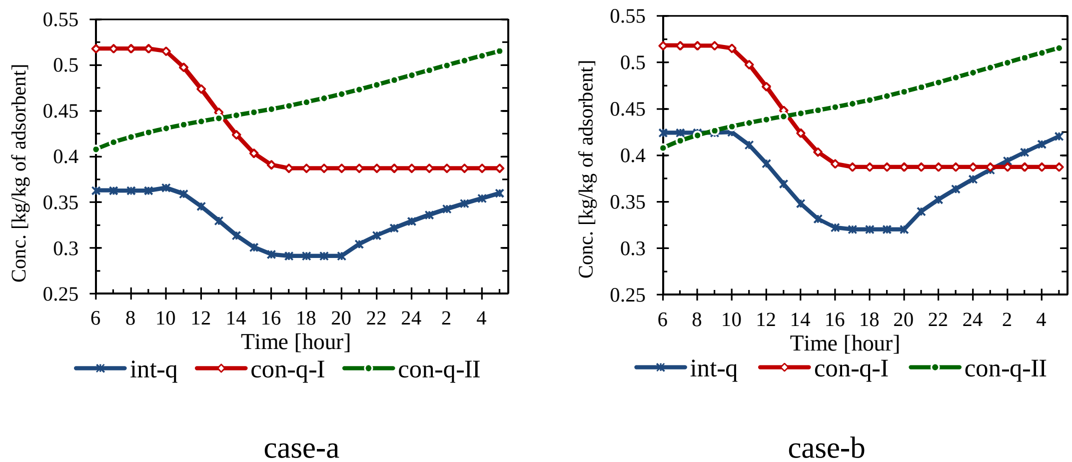


**Fig. (11).** Comparison betweenrefrigerant concentration in the beds of intermittent and present continuous system.

this way both system has same size but the bed size connected to the evaporator in intermittent system become double compare to the bed size connected to evaporator in continuous system. Therefore, in case-b, the size of the bed in intermittent system was kept equal to the one bed in continuous system. In this way, bed size connected with evaporator was same in both systems but total size of beds become twice in the continuous system compare to the intermittent system.

Fig. (**10**) shows the comparison between system temperatures of intermittent and continuous system for one day operation. It can be noted that the bed temperature for continuous system (res dotted line) is lower than the bed temperature of intermittent system (red complete line) in both cases. This is because the more amount of refrigerant is desorbing at faster rate from the continuous bed compare to the intermittent bed as shown from Fig. (**11**). Desorption is endothermic process, therefore, the bed temperature decreases according to desorption rate. There is no significant difference in condenser temperature of intermittent and continuous system in both cases. The evaporator temperature for intermittent system is different for two cases compare with continuous system. For the case-a, where the bed size is same in both systems, the difference in evaporator temperature for intermittent and continuous system is small. But still the continuous system maintains the low temperature throughout the day compare to the intermittent system where the evaporator temperature increases during day. It should be remember that in intermittent system cooling is not produced during the day time because evaporator is connected only at night time, while in continuous system the evaporator is connected all the time to shaded bed and cooling is produced continuously as shown in Fig. (**12**).

On the other hand, for the case-b, where the same bed sizes were connected with evaporator, there is significant difference in evaporator temperatures. The continuous system always keeps the evaporator temperature lower than evaporator temperature in intermittent system, and maximum difference of 10 °C was found between two temperatures.

It can be summarized from the above comparison that if the same amount and size of the system is considered, con-

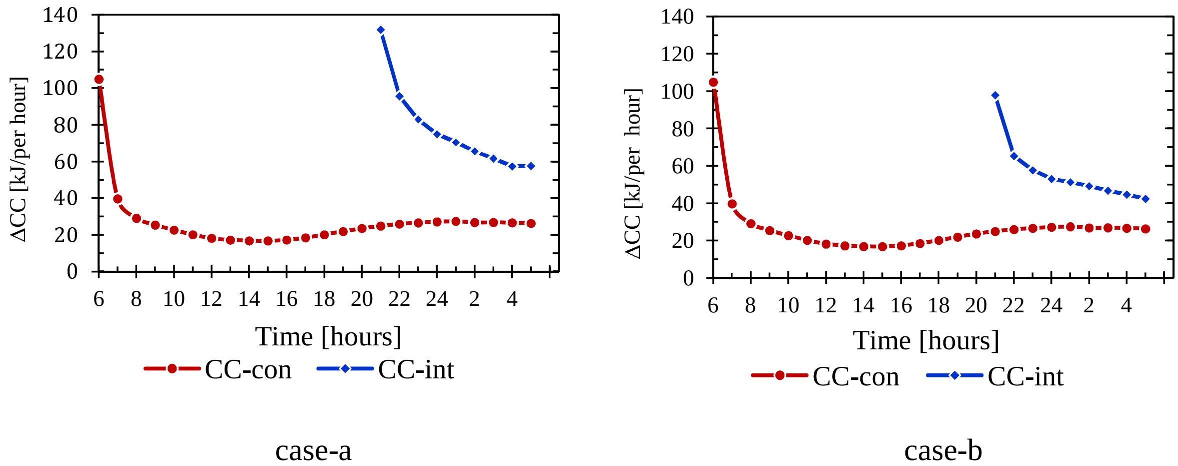


**Fig. (12).** Comparison between change in cooling capacity of intermittent and present continuous system.

tinuous cooling can be achieved but effect is small. If continuous cooling is the primary objective than double size of the bed is required for significant effect.

## 6. CONCLUSION

In this article, simulation study of a solar adsorption refrigeration system was presented that produce cooling continuously using only solar energy as driving force. The conventional one bed system work intermittently, day time it desorbs refrigerant and produced cooling only at night time. But basically cooling demand increases during the day time when outside is hot. The proposed system consists of two beds with CPC collectors, a condenser and evaporator. In one day operation one bed was shaded and connected with evaporator while other works normally. Next day the beds were interchanged and same operation was repeated. In this way one cycle completed in two days and continuous cooling produces because evaporator was always connected with one of the beds. There are very fewer studies related to such continuous system, but no work was found that investigate the actual behaviour of the solar adsorption refrigeration system producing cooling continuously using only solar energy. The objectives of the study were to investigate the actual behaviour of the system especially the adsorption behaviour during day period when ambient temperature is high, and to compare the performance of the system with conventional intermittent system. A detailed simulation model was developed that uses the actual measured weather data for Tokyo, Japan. The simulation results can be summarised as follow;

- The system achieves low temperature in the evaporator throughout the day and night, although the cooling capacity is low but continuous cooling is attractive.
- The cooling rate changes according to the adsorption rate of refrigerant. In the peak day hours when the ambient temperature was relatively higher, the adsorption rate became slower because of slow heat rejection to ambient. The temperature of the shaded adsorbent bed increases when the adsorption rate increases.
- The ice was not produce during the process indicating the amount of desorbed refrigerant that were coming to evaporator was not enough to bring the water temperature below 0 °C.
- The estimated specific cooling effect of the system was found to be110.5 kJ/kg of adsorbent in one bed that is equivalent 7.67 W/day or 1.27 W/Kg of adsorbent or 30.7 W/m$^2$ of the each CPC aperture area for $L_{CPC}$ = 2m/CPC, $M_{ACF}$ = 3kg/$L_{CPC}$ and $U_{bed}$ = 25W m$^{-2}$ K$^{-1}$
- The performance of the system increases with high value of coefficient of heat transfer between CPC receiver and adsorbent bed ($U_{bed}$). This means the use of heat transferring medium into bed and adsorbent with high thermal conductivity are preferred. On the other hand the performance decreases by increasing the adsorbent mass ($M_{ACF}$).
- The performance of the continuous system was compared with performance of intermittent system. The significant difference is the intermittent system produce cooling only during night while the proposed system produced continuous cooling. For the case when both system has same bed size the difference in evaporator temperatures was small compare to the case when evaporator was connected with same size of beds in both system. It was found that continuous system keeps the evaporator temperature maximum 10 °C lower than the intermittent system.

It can be concluded that the continuous cooling can be achieved with such system. But still more investigation is needed to evaluate the system performance, specially the experimental investigation of adsorption rate in the shaded bed during day time. Some heat rejecting mechanism is needed for the shaded bed to increase the adsorption rate that can be done by opening the cover or attaching the fins to the shaded CPC. System can be used for refrigeration or cooling purposes but difficult for continuous ice making until some high efficient working pair with optimized system design is used. This study will facilitate and motivate the future researches in solar adsorption continuous refrigeration technology because achieving continuous cooling even at low rate; only with solar energy is very attractive, especially in the developing and remote areas.

## ABBREVIATIONS AND SYMBOLS

| A | area ($m^2$) | Subscripts | |
|---|---|---|---|
| $C_P$ | specific heat (J $kg^{-1}$ $K^{-1}$) | *ACF* | activated carbon fibber |
| CC | cooling capacity (kJ) | *air* | air |
| con | continuous system | *ap* | aperture |
| D | exponential constant ($K^{-2}$) | *bed* | adsorbent bed |
| F | control factor (1 or 0) | *bm* | beam |
| $h_{Rr}$ | radiation heat transfer coefficient between receiver and cover (W $m^{-2}$ $K^{-1}$) | *c* | condenser |
| $h_{Rs}$ | radiation heat transfer coefficient between cover and sky (W $m^{-2}$ $K^{-1}$) | *cov* | CPC cover |
| $h_{rc}$ | convective heat transfer coefficient between cover and receiver (W $m^{-2}$ $K^{-1}$) | *cpc* | CPC collector |
| $h_{ca}$ | convective heat transfer coefficient from cover due to wind (W $m^{-2}$ $K^{-1}$) | *Cu* | Copper |
| $\Delta H_{st}$ | heat of adsorption/desorption (J $kg^{-1}$) | *diff* | diffuse |
| I | solar radiation (W $m^{-2}$ ) | *e* | evaporator |
| int | intermittent system | *ice* | ice |
| $k_s a_v$ | overall mass transfer coefficient ($S^{-1}$) | *re-e* | refrigerant in evaporator |
| $L_H$ | latent heat of vaporization (J $kg^{-1}$) | *re* | refrigerant ethanol |
| M | mass (kg) | *w* | water |
| P | pressure [Pa] | *wt* | water tank |
| Ps | saturation pressure [Pa] | Superscripts | |
| q | instantaneous uptake (kg $kg^{-1}$) | *a* | adsorption |
| SCE | specific cooling effect [k J $kg^{-1}$] | *d* | desorption |
| T | temperature [K] | *nr* | average number of reflections |
| $U_{bed}$ | overall heat transfer coefficient between receiver and adsorbent bed (W $m^{-2}$ $K^{-1}$) | | |
| $U_e$ | overall heat transfer coefficient between evaporator and ambient (W $m^{-2}$ $K^{-1}$) | Greek letters | |
| $U_w$ | overall heat transfer coefficient between evaporator and water tank (W $m^{-2}$ $K^{-1}$) | $\alpha$ | absorptance |
| $U_\beta$ | overall heat transfer coefficient between water tank and ambient (W $m^{-2}$ $K^{-1}$) | $\theta_i$ | angle of incident |
| W | uptake of refrigerant (kg $kg^{-1}$) | $\rho$ | reflectance |
| $W_o$ | maximum uptake (kg $kg^{-1}$) | $\tau$ | transmittance |

## CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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