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Improved cooling capacity of a solar heat driven adsorption chiller

R.A. Rouf [a,*], N. Jahan [b], K.C.A. Alam [c], A.A. Sultan [a], B.B. Saha [d], S.C. Saha [c]

[a] Department of Physical Sciences, School of Engineering and Computer Science, Independent University, Bangladesh
[b] Department of Science and Humanity, Bangladesh Army International University of Science and Technology, Bangladesh
[c] School of Mechanical and Mechatronics Engineering, University of Technology, Sydney, NSW2007, Australia
[d] International Institute for Carbon-Neutral Energy Research (WPI-I2CNER), Mechanical Engineering Department, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka-shi, Fukuoka, 819-0395, Japan

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ABSTRACT

This paper discusses two investigations which indicate the benefit of exploiting multiple adsorption containers to increase the cooling energy output of a limited supply of solar heat. First, the optimum working conditions on the output of a solar-powered 3-bed adsorption cooling scheme working in a series and secondly, the performance of a new parallel system of 4-beds has been investigated. It is seen that especially when the source of heat is limited, the output of solar assisted adsorption cooler can be enhanced if the total amount of adsorbent can be distributed in three identical small adsorption beds. As a continuation of the study with multiple beds, the performance of a newly proposed cooling unit with 4-beds has also been studied. This parallel system of 4-beds is considered in such a way that, when one conventional 2-bed chiller is in adsorption/desorption mode then the other chiller is in the preheat/pre-cool mode and the system goes on alternately. Both of these chillers are linked with a single evaporator and condenser, resulting in a continuous evaporation and condensation process. Both of these new systems with multiple beds can utilize maximum entropy as exploits a longer precool time and improves specific cooling capacity (SCC).

1. Introduction

It had been almost five decades since adsorptive heat transformation (AHT) gained attention in the field of emergence in the present and future world. Adsorption refrigeration/space cooling method considered as green cooling technology has attracted interest as to reduce energy consumption and protection of environmental aspects. Since it uses non-fossil energy, this technology contributes to the reduction of CO_2 emission. Thus, adsorption refrigeration machines have two significant advantages; they are environment-friendly since there is no Ozone Depleting Potential (ODP) and no Global Warming Potential (GWP). Generally, the cold production in the basic cycle of adsorption refrigerating machines is irregular. Advanced cycles are necessary to achieve higher efficiencies and uninterrupted cold production. Some of these advanced cycles are heat recovery cycle [1–4], mass recovery cycle [5–9], both heat and mass recovery cycle [2,10,11]. Very recently, a numerical investigation has been conducted by Nasruddin et al. [12] to predict the performance of solar absorption chiller based on the selection of the principal components by Artificial Neural Network (ANN).

Water purification and desalination with the application of adsorption technology can serve to reduce the crisis of drinking water (Saha et al. [13]), particularly in the middle-east countries. In the recent year's development of sorption materials and prototypes had

* Corresponding author.
E-mail address: rifatara@iub.edu.bd (R.A. Rouf).

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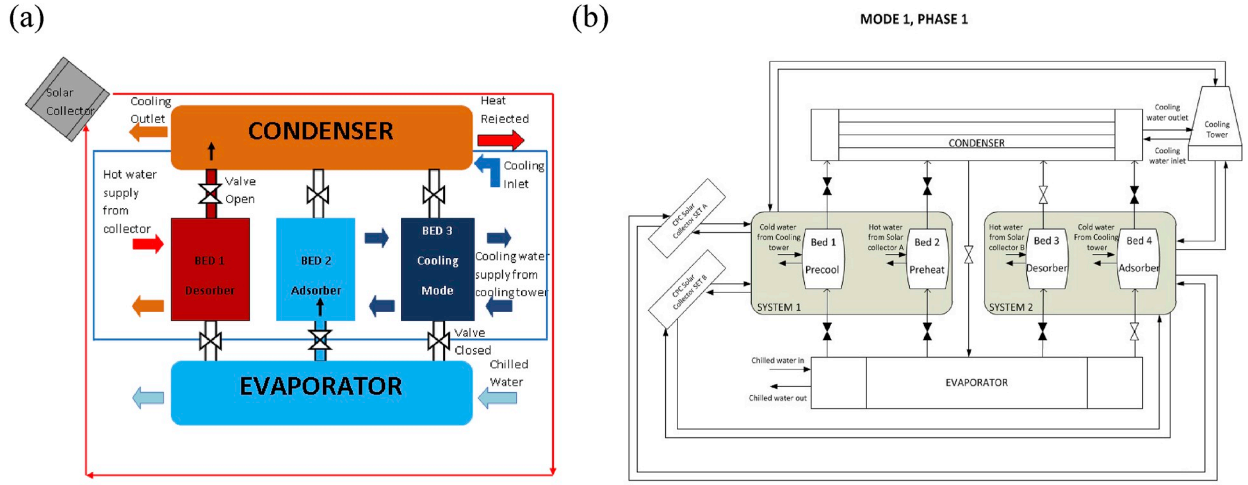

Fig. 1. (a) Schematic diagram of 3-bed system working in a series (source [18]), (b) schematic diagram of the 4-bed parallel system.

Table 1
The working rule of the 4-bed parallel scheme.

Mode of the bed	Bed 1	Bed 2	Bed 3	Bed 4
Mode 1, phase 1 (120s)	Pre-cool	Preheat	Desorber	Adsorber
Mode 1, phase 2 (120s)	Adsorber	Desorber	Pre-cool	Preheat
Mode 2, phase 1 (120s)	Preheat	Pre-cool	Adsorber	Desorber
Mode 2, phase 2 (120s)	Desorber	Adsorber	Preheat	Pre-cool

Table 2
Connection of the collector sets with the two systems at different phase in a mode.

Mode 1	Collector	System
Phase 1	Set A	1 (desorber in preheat)
	Set B	2 (desorber in desorption)
Phase 2	Set A	2 (desorber in preheat)
	Set B	1 (desorber in desorption)

been investigated for long term heat storage from low-temperature heat source [14–16]. Aristov [17] proposed a new cycle by reducing the vapour pressure at a persistent temperature rather than increasing temperature of the adsorbent; he mentioned this new cycle as “Heat from Cold”. Rouf et al. [18] introduced a 3-bed conventional cycle where the three adsorbent beds are considered to be functioning as an adsorber and a desorber in a cyclic order.

This article focused on the advantage of using relatively smaller multiple adsorption beds and distributing the total amount of adsorbent into them in order to exploit lesser amount of available solar energy to increase cooling output. A new 3-bed cycle working in a series had been introduced by Rouf et al. [18] previously. The performance of this cycle was encouraging when low heat input had been considered. As a continuation of this study, the optimum operating condition of this 3-bed adsorption cycle working in a series and also a 4-bed parallel system had been investigated in order to ensure maximum utilization of entropy and continuous process of evaporation and condensation. This new cycle will be effective for not only low-grade heat input but also for a limited amount of adsorbent.

2. System description

The schematic diagram of two systems are presented in Fig. 1. The working principle and operating conditions of the 3-bed system

Table 3
Change in the base run conditions for the 4-bed parallel system.

Symbol	Description	Value
A_{bed}	Heat transmission area of bed as adsorbent	$1.23m^2$
M_s	Mass of silica gel/bed	23.5 kg

(Fig. 1. (a)) can be found in Ref. [18] and a new 4-bed system is introduced in Fig. 1. (b).

For the newly proposed 4-bed chiller, two conventional 2-bed solar heat assisted adsorption chiller has been joined. There are four adsorption beds, one evaporator, and one condenser. According to Fig. 1(b), system one is in the pre-heat/precool mode. Meanwhile, system two is in desorption/adsorption mode and connected with both condenser and evaporator. The action of the combined system is described in Table 1.

In order to keep a steady amount of heat supply to the desorber when in the pre-heat and desorption phase, two different sets of collectors have been chosen. The connection between the two systems with the two sets of CPC collectors is described in Table 2.

The base run conditions have a little change with that of Rouf et al. [18] for the new 4-bed system. The base run conditions can be found in Table 2 Rouf et al. [18]. The changes considered here are given in Table 3.

3. Mathematical formulations

The heat collected by a solar thermal collector, which is manufactured by Ritter Solar known as compound parabolic concentrator CPC1509, is exploited as the heat source for the cooling unit.

The collector efficiency equation is (as [19]):

$$\eta = 0.64 - 0.89\left(\frac{T_f - T_{am}}{I}\right) - 0.001\left(\frac{T_f - T_{am}}{I}\right)^2 \tag{1}$$

Solar irradiance data, collected from Renewable energy research center (of the University of Dhaka), has been simulated by a sine function as [19]. Two sets of collectors have been considered in this study. Where each set of collectors are joint in separate series. Heat transporter liquid (water) is equally circulated in the collectors. Each of these collectors has nine pipes, the outflow of the first pipe of every single collector enters the second pipe of that collector, and by this process, the outflow of the ninth pipe is the inflow of the first pipe of the next collector. Accordingly, the outflow of the last pipe of the last collector of the series (namely set A) flows in the desorber in the preheat phase. However, the other set of collectors (collector set B), arranged in the same way, supplies heat to the desorber in the desorption phase. Therefore the heat of the heat transporter fluid in every single pipe is independently calculated for all the solar thermal collectors. Hence the energy balance of every single collector is stated as:

$$M_{cp,k}c_{p,cr}\frac{dT_{cr,k}}{dt} = \gamma\left\{\eta_k A_{cr,k} I + \tilde{m}_{f,cr}c_{p,f}\left(T_{cr,k,in} - T_{cr,k,out}\right)\right\} + (1-\gamma)U_{tuM,loss}A_{cr,k}\left(T_{am} - T_{cr,k}\right) \tag{2}$$

$$T_{cr,k,out} = T_{cr,k} + \left(T_{cr,k,in} - T_{cr,k}\right)\exp\left(U_{cp,k}A_{cp,k} \big/ \tilde{m}_{f,cr}c_{p,f}\right) \tag{3}$$

where, $k = 1, \ldots, 9$. γ is 1 during daytime and 0 at nighttime, respectively.

Adsorption rate is dependent on the outer surface area and thermodynamic properties of the adsorbent. In this study uptake rate of specially researched and then developed (RD) type silica gel-water pair is calculated by LDF (linear driving force) model. This is a nonlinear equation in terms of pressure and temperature. The pressure and temperature throughout all the heat transfer units have been chosen as uniform. Therefore, In order to model the energy balance equations, the lumped parameter model has been used. The energy balance equations for all heat exchangers can be found in Ref. [18].

Hence, one can calculate the balance of the total mass of refrigerant inside the **e**vaporator as:

$$\frac{dW_{eva,w}}{dt} = -W_s\left(\frac{dq_a}{dt} + \frac{dq_d}{dt} + \frac{dq_{coolingbed}}{dt} + \frac{dq_{heatingbed}}{dt}\right) \tag{4}$$

At last, the average cooling capacity in a cycle is calculated by the equation:

$$CACC = TotalQ_{coolout/cycle} \big/ t_{cycle}W_s \tag{5}$$

The specific cooling capacity per cycle $SSC$is calculated as:

$$SSC = TotalQ_{coolout/cycle} \big/ \left(t_{cycle}W_s\right) \tag{6}$$

The solar coefficient of performance is calculated as:

$$COPsolar = TotalQ_{coolout/cycle} \big/ TotalQ_{hotin/cycle} \tag{7}$$

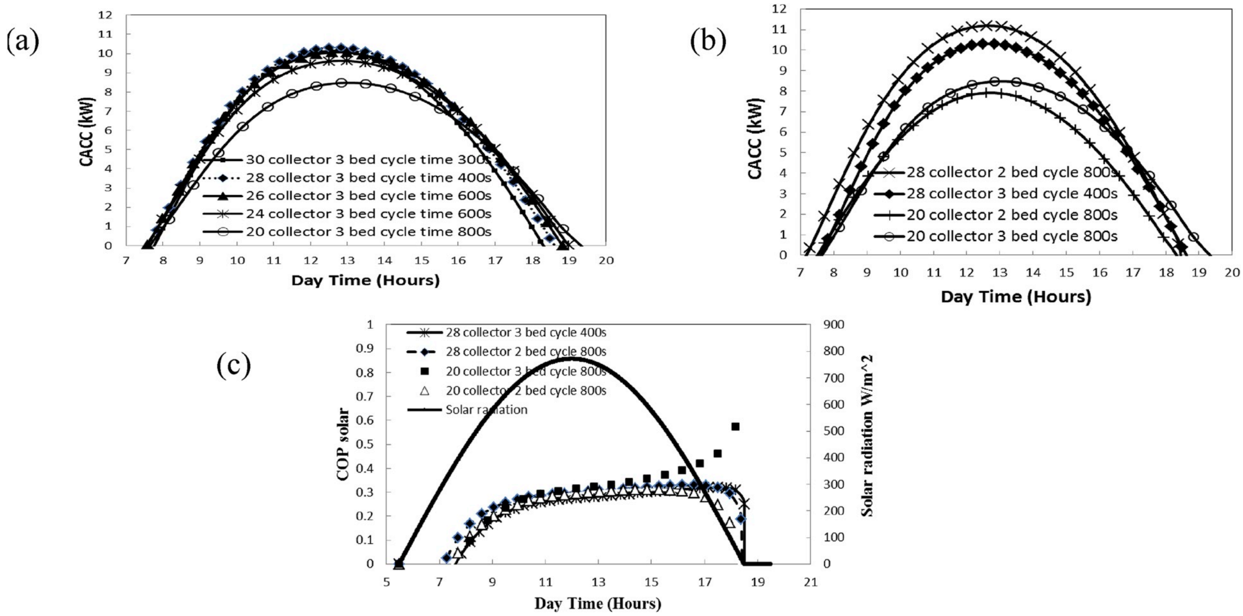

Fig. 2. a) CACC for 3-bed system with different collector area and cycle time, b) CACC for 3-bed and 2-bed system for optimum collector area and cycle time and c) COPsolar for 3-bed and 2-bed system for optimum collector area and cycle time and daily solar radiation data.

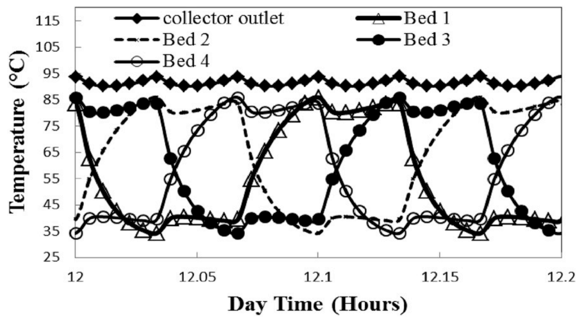

Fig. 3. Temperature history of collector set B outlet and 4 beds.

4. Methodology

During the simulation, tolerance for all the convergence criteria have been considered as 10^{-4}. Solar radiation data of the month of April for the station of Dhaka (Latitude 23.46 N, Longitude 90.23 E) has been used, where average (7 years from 2003 to 2010) maximum radiation in April is considered as 988 W/m^2. The sunrise time and the sunset time of this month is considered at 5.5 h and 18.5 h respectively and maximum temperature 34 °C, minimum temperature 24 °C. In order to solve the set of differential equations implicit finite difference approximation method has been applied. The chiller configurations and environmental data set are same as Rouf et al. [18].

The simulation procedure can be found in Ref. [15]. The numerical results of the proposed simulation are calculated by Logical programming language FORTRAN with Compaq visual Fortran compiler.

5. Results and discussion

For the 3-bed adsorption cooling cycle, the optimum operating condition is 28 solar thermal collectors each of area 1.72 m^2 with cycle time 400s. According to Fig. 2. (a), with increasing collector area cooling capacity (CACC) increases. But there is a very little improvement of the cooling capacity after increasing collector number from 26 to 30. Maximum cooling capacity can be noticed for collector number 28. Since for extensive heat input temperature of the heat transfer unit gets heated in a shorter cycle time, therefore, it is evident that the cost of the cooling system can be reduced by choosing longer cycle time and a smaller collector area. However. with the optimum operating conditions, for 3-bed chiller the obtainable CACC is 10.3 kW, which is lower than that of the conventional 2-bed basic system (CACC 11.19 kW) with identical operating conditions, Fig, 2. (b). The cooling capacity of 3-bed chiller is less than

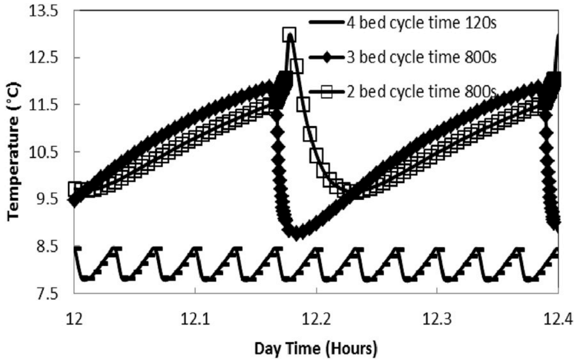

Fig. 4. Collector area 34.4 m^2. Comparative evaporator outlet temperature of 4-bed cycle time 120s, 3-bed cycle time 800s and 2-bed cycle time 800s.

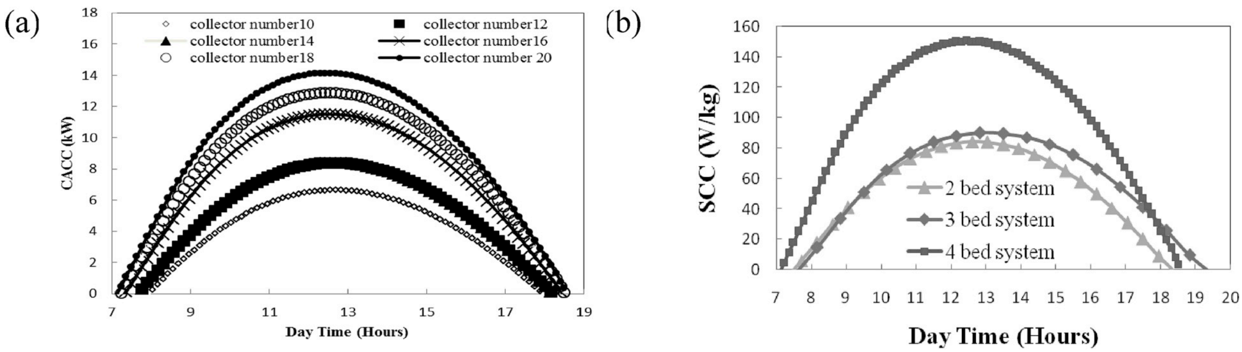

Fig. 5. (a) Comparative cooling capacity of 4-bed system with different number of collectors cycle time 120s, (b) comparative specific cooling capacity of the three different systems with 34.4 m^2 collector area.

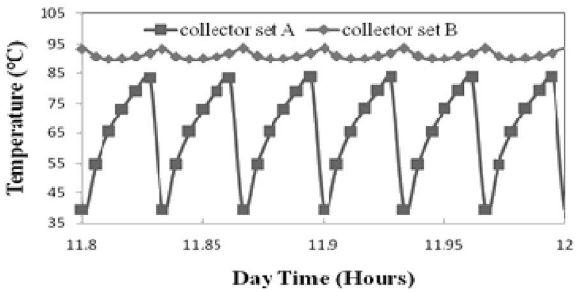

Fig. 6. Comparative temperature profile of collector set A and B.

that of a 2-bed chiller due to the small amount of adsorbent in each smaller bed. With maximum heat input, for 3-bed chiller bed temperature rises rapidly. Therefore, the system cannot take longer cycle time, in other words precooling time, consequently the thermal gradient of the bed is not large enough which results in a small entropy of the adsorber and ended with comparatively lesser cooling capacity. Conversely, when there is less heat input (34.4 m^2, 20 collector area) and longer cycle time, the result is just opposite since this time the thermal gradient is large. Therefore, the cooling capacity 8.47 kW is gained with 3-bed distributed mass, whereas it is only 7.91 kW with a 2-bed conventional system. These results lead to the thought that with a small amount of heat input, better output could be found if the total amount of adsorbent can be distributed into multiple adsorption beds and a longer precooling time. Maximum COPsolar is reported for a 3-bed system with 20 collectors (34.4 m^2 collector area) and cycle time 800s, Fig. 2. (c). The figure shows an increasing value of COPsolar for this case. Since at the end of the day there is no more solar radiation available but the cooling production is still working calculated COP at this time is high.

However, keeping this ideal heat input (20 collectors), a second choice had been adopted in order to study the performance with 4 adsorption beds. The temperature history of the new 4-bed system is presented in Fig. 3. According to the figure when bed 1 is in the pre-cool mode bed 2 is in the preheat mode, bed 3 is in the desorption mode, and bed 4 is in the adsorption mode. Each bed contains

23.5 kg of RD type silica gel, hence the cycle time is very short (120s for each phase).

Fig. 4 shows that there is almost a steady temperature (8 °C) for evaporator outlet with 4-bed system. The cooling capacity for 14 and 16 collectors are almost overlapping but for shorter cycle and larger collector area CACC increases (Fig. 5 (a)). The optimum cooling capacity with the 4-bed parallel system is found to be 14 kW with 20 collectors (34.4 m^2 collector area) with optimum full cycle time 480s Fig. 5 (a). Specific cooling production is better than all other cases and collector set B is always connected in the desorption phase, there is more fluctuation in the temperature of the collector set A compared to that of collector set B (Fig. 6). This choice of two sets of collectors, connected with two desorbers in a different phase, ensures steady heat input during the desorption phase and confirms better desorption kinetics. As a result, the entropy of the adsorbent can be better utilized.

6. Conclusions

The optimum operating conditions of an earlier introduced 3-bed distributed mass system working in a series and a new 4-bed distributed mass parallel adsorption cooling chiller has been discussed in detail. Based on the discussion following conclusions can be drawn;

- For low-grade heat input, encouraging performance is observed for distribution of the adsorbent mass in multiple beds and lengthened pre-cooling time.
- The best cooling output is observed for a 4-beds parallel system with a full cycle time of 480s.
- Maximum SCC is 150 W/kg at the pick hours for a 4-beds parallel system.

For a densely populated tropical country like Bangladesh, in order to mitigate the energy crisis, adsorption technology can be an important opportunity. Abandoned solar energy can be an appropriate source of energy to support adsorption cooling, refrigeration and water purification system. Wise utilization of this technology can help to deal with the limitation of free space and reduce the installation cost.

Declaration of competing interest

There is no conflict of interest between the authors and/or any organization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csite.2019.100568.

Nomenclature

A	area (*m^2*)
CACC	cyclic average cooling capacity (*kW*)
COP	coefficient of performance
cp	specific heat energy (J/kgK)
I	solar radiation (W/m^2)
M	mass (*kg*)
$\tilde{m}$	rate of mass flow (kg/s)
q	adsorption capacity (*kg/kg* silica gel)
Q	energy
SCC	specific cooling capacity (W/kg)
t	time (*s*)
T	temperature (*K*)
U	coefficient of heat transfer (W/m^2 K)
W	total mass of refrigerant (water)

Subscripts

a	adsorber
am	ambient
bed	bed full of adsorbent
Coolingbed	bed in the cooling mode
cr	collector
d	desorber

f	heat transfer fluid (water)
s	silica gel
tuM	tube metal
w	water

Greek symbols

γ	logical parameter
η	efficiency of compound parabolic concentrator (CPC) solar collector

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