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Study on the effect of Multiple Beds Operation Scheme for Performance Enhancement in Solar Heat-Driven Adsorption Chiller

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Abstract

The severity of the ozone layer destruction problem has called for rapid developments in environmentally friendly air conditioning technologies. Ongoing deregulatory efforts in the Organization for Economic Co-operation and Development (OECD) nations will ease the penetration of thermally activated heat pump systems. Absorption (liquid-vapor) and adsorption (solid-vapor) heat pump systems are thermally driven and have the advantage of being environmentally benign: both their ODP (Ozone Depletion Potential) and their GWP (Global Warming Potential) are zero. Adsorption cycles using silica gel-water as the adsorbent-refrigerant pairs have a distinct advantage over other systems in their ability to be driven by the heat of relatively low, near-ambient temperatures so that waste heat below 100˚C can be recovered. The multi-bed multi-stage silica gel-water-based adsorption systems can be powered by low-temperature waste heat below 100˚C, even as low as 50˚C if the multi-stage regenerative scheme is adopted.

Subject Areas

Industrial Engineering

Keywords

Adsorption Cooling, Heat Transfer, Solar Heat

1. Introduction

Adsorption refrigeration technologies exploit waste heat to produce cooling; thus reducing fossil fuel consumption and CO_2 emissions. Solar heat is one of the most effective and suitable sources of energy to activate an adsorption cooling unit that is run by low-grade heat. Alam *et al.* [1] showed that if the heat source temperature is greater than 60˚C, then COP of a two-stage scheme. Habib *et al.* [2] studied various sorption pairs for solar adsorption-cooling applications. The study revealed that, for low regeneration temperatures, the silica gel/water pair is recommended to obtain a high coefficient of performance COP-value. Recently, Chekirou *et al.* [3] numerically investigated several main factors that affect the outcome of cycles. Mainly, regenerating consideration and evaporation temperature are also the difference in temperature among the two adsorber beds when the heat recovery mode ends.

Studies on the development of adsorption technologies, working pairs and sorption engines powered by waste heat or solar-powered adsorption can be found in the literature [1] [4]-[9]. Different designs and multiple heat transfer units have been studied for performance analysis of adsorption refrigeration and cooling units [10]-[15].

Conventional two-bed basic adsorption cooling and refrigeration systems run by solar heat are well established for their working principle and environment-friendly operations. But the main challenge for this system is the huge footprint. Starting from the solar heat collection unit to the organization of the adsorption cooling unit, it occupies a large space for installation. Therefore, one needs to concentrate on the optimization of the size of the system and utilization of low energy. The proposed study will discuss the advantage of disseminating the adsorber beds into smaller multiple beds, which can perform better with a lesser amount of solar heat.

Adsorption refrigeration/space cooling method considered as a green cooling technology has attracted interest as to reduce energy consumption and protecting of environmental aspects. Since it uses non-fossil energy, this technology contributes to the reduction of CO_2 emissions. Thus, adsorption refrigeration machines have two important 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. For intermittent cycles, Qasem and El-Shaarawi [16] [17] inspected the impact of consuming different types of activated carbon and different operating condition numerically also Souissi *et al.* [18] presented experimental outcomes for a model irregular solar adsorption ice-maker where silica-gel water pair was used as adsorbent and adsorbate.

The cascading adsorption scheme is testified to improve the COP of 2-bed intermittent cycles [19] [20] [21]. This system can further improve both the COP and SCP by using a combined evaporator/condenser in two cycles in which multiple beds are utilized to cause nonstop cooling. Habib *et al.* [22] studied a 4-bed adsorption refrigeration scheme. This system was designed from two different systems exploiting working pairs; activated carbon/R507A topped by activated carbon/R134a. In this work, he investigated the optimum operating conditions for the low regenerative temperature of 70˚C and found a −10˚C refrigeration load. Meunier [23] theoretically considered cascading adsorption of four adsorbers with four configurations, two condensers and two evaporators. The study was done for a different generation and evaporation temperatures and achieved evaporator temperature of −10˚C. Here, two different adsorbent/adsorbate pairs had been utilized. One was zeolite-water, and the other one was activated carbon-methanol. For vaccine storage, Dawoud [24] theoretically developed a hybrid solar-adsorption refrigeration system; here he united two adsorption cycles to attain refrigeration at low temperatures. Oliveira *et al.* [25] examined experimentally an adsorption ice-making system with four-bed, a single condenser and a single evaporator along with an activated carbon/ammonia working pair in which desorption temperature was ranging from 85˚C - 115˚C and evaporator temperature as low as −27˚C. An adsorption freezing unit of the double stage has been experimentally investigated by Wang *et al.* [26] by means of three levels of heat source temperatures of 75˚C, 80˚C and 85˚C with evaporator outlet temperatures of −5˚C, −10˚C and −15˚C respectively. In this study, they utilized chemical adsorbents $CaCl_2$ and $BaCl_2$ paired with ammonia. Wang developed this system by mingling Organic Ranking Cycle with the system introduced by Jiang *et al.* [27] to utilize waste heat using a cascading technique. In this connection, the advanced cycle with multiple beds was proposed for a better cooling effect by Wirajati *et al.* [28]. The substantial amounts of waste heat were produced from power generation and industrial processes at temperatures below 100˚C. The exploitation of waste heat can lead to a significant reduction in fossil fuel consumption and CO_2 emissions. Lately, Dakkama *et al.* [29], using diverse working pairs, inspected the performance of a combined evaporator-condenser cascaded adsorption system that can exploit this waste heat for low-temperature cooling.

2. System Description

The operation process of a two-bed conventional solar-assisted chiller is available in the literature [30]. The operating conditions of the three-bed chiller had been discussed by Rouf *et al.* [31]. A new four-bed cooling unit has been considered by Rouf *et al.* [32] in such a way that two separate two-bed conventional cooling units is working alternately utilizing a single condenser and an evaporator. Therefore, there remains a continuous process of evaporation and condensation. Hence, for the choice of this four-bed system better cooling production is available. The schematic diagram of the three systems is presented in **Figure 1(a)**, **Figure 1(b)** and **Figure 1(c)** respectively.

According to **Figure 1(c)**, system one contains Bed 1 and Bed 2 and system two contains Bed 3 and Bed 4. Both systems are linked with the same condenser and the evaporator, the cooling tower, and two different sets of CPC solar thermal collectors. Collector Set A is connected with the desorber in preheat mode and Collector Set B is connected with desorber in the desorption mode. Therefore, according to the table Collector Set A is always connected in the preheat phase, and Collector Set B is always connected in the desorption phase.

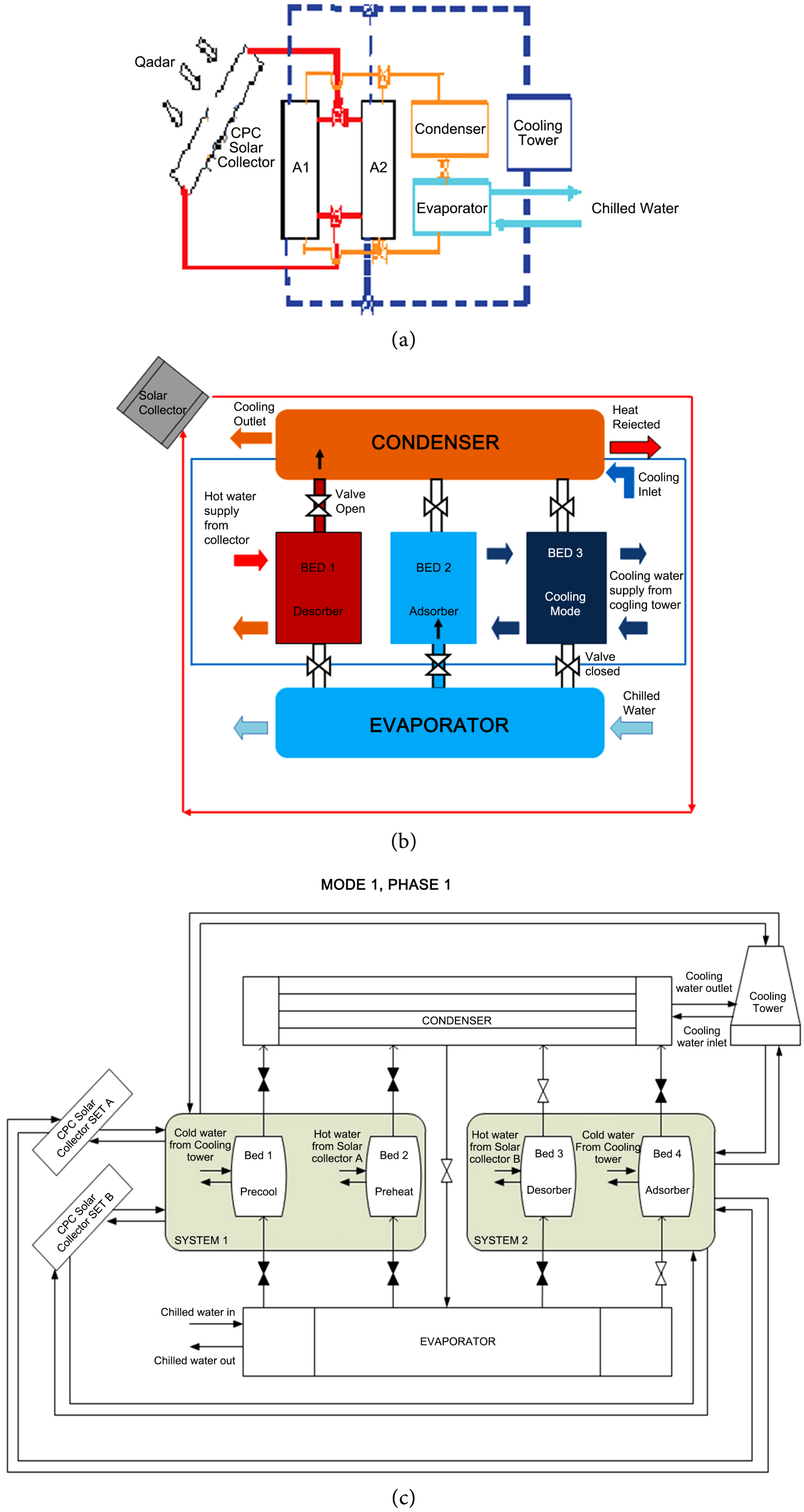

Figure 1. Schematic diagram of (a) conventional two-bed basic adsorption chiller [2], (b) three-bed distributed mass chiller [3] and (c) four-bed parallel chiller.

3. Mathematical Model

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:

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

$$T_{cr,k,out}=T_{cr,k}+\left(T_{cr,k,in}-T_{cr,k}\right)\exp\left(U_{cp,k}A_{cp,k}/\tilde{m}_{f,cr}c_{p,f}\right) \tag{2}$$

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

The energy balance equations of all the heat transfer units can be found in the literature [13]. The numerical results of the proposed simulation are calculated by Logical programming language FORTRAN with Compaq visual FORTRAN compiler.

The balance of the total mass of refrigerant inside the **e**vaporator for two-bed conventional basic chiller is:

$$\frac{\mathrm{d}W_{eva,w}}{\mathrm{d}t}=-W_s\left(\frac{\mathrm{d}q_a}{\mathrm{d}t}+\frac{\mathrm{d}q_d}{\mathrm{d}t}\right) \tag{3}$$

Hence, one can calculate the balance of the total mass of refrigerant inside the evaporator for three-bed and four-bed chillers as:

$$\frac{\mathrm{d}W_{eva,w}}{\mathrm{d}t}=-W_s\left(\frac{\mathrm{d}q_a}{\mathrm{d}t}+\frac{\mathrm{d}q_d}{\mathrm{d}t}+\frac{\mathrm{d}q_{\mathrm{coolingbed}}}{\mathrm{d}t}\right) \tag{4}$$

and

$$\frac{\mathrm{d}W_{eva,w}}{\mathrm{d}t}=-W_s\left(\frac{\mathrm{d}q_a}{\mathrm{d}t}+\frac{\mathrm{d}q_d}{\mathrm{d}t}+\frac{\mathrm{d}q_{\mathrm{coolingbed}}}{\mathrm{d}t}+\frac{\mathrm{d}q_{\mathrm{heatingbed}}}{\mathrm{d}t}\right) \tag{5}$$

respectively.

The radiation of the sun has been simulated as a sine function:

$$I=I_{\max}\sin\left(\frac{\pi\left(\text{daytime}-\text{sunrisetime}\right)}{\text{sunsettime}-\text{sunrisetime}}\right). \tag{6}$$

The performance of a four-bed adsorption chiller with mass recovery is mainly characterized by Average Cooling Capacity (CACC) and Specific Cooling Capacity (SCC) and solar coefficient of performance (COP_{solar}), waste heat recovery efficiency (η) and can be measured by the following equations:

The average cooling capacity in a cycle is calculated by the equation:

$$\text{CACC}=\text{Total }Q_{\text{coolout/cycle}}/t_{\text{cycle}} \tag{7}$$

The Specific Cooling Capacity (SCC) is calculated as:

$$\text{SCC}=\text{Total }Q_{\text{coolout/cycle}}/\left(t_{\text{cycle}}W_s\right) \tag{8}$$

The solar coefficient of performance is calculated as:

$$\text{COP}_{\text{solar}}=\text{Total }Q_{\text{coolout/cycle}}/\text{Total }Q_{\text{hotin/cycle}} \tag{9}$$

And the waste collector efficiency equation is:

$$\eta = 0.64 - 0.89\left(\frac{T_f - T_{am}}{I}\right) - 0.001\left(\frac{T_f - T_{am}}{I}\right) \tag{10}$$

4. Results and Discussion

The optimum collector area for a two-bed conventional basic adsorption chiller with silica gel/water pair run by direct solar coupling is 28 CPC collector of area 47.6 m^2 [14]. But installation of solar thermal collector of such a large number is sometimes not possible. Therefore, in need of an alternative way to utilize as much solar energy available to gain maximum chilling output, total amount of adsorbent has been disseminated into multiple adsorber beds of smaller corresponding vessels. **Figure 2(a)**, **Figure 2(b)** and **Figure 2(c)** illustrates the bed temperature at the pick hours when two-bed, three-bed and four-bed chillers had been used respectively. The temperature gradient inside the adsorber is one of the key factors of the performance of the chiller. According to **Figure 2**, the temperature gradient for the chiller with three-bed and four-bed system is greater than that of the two-bed system.

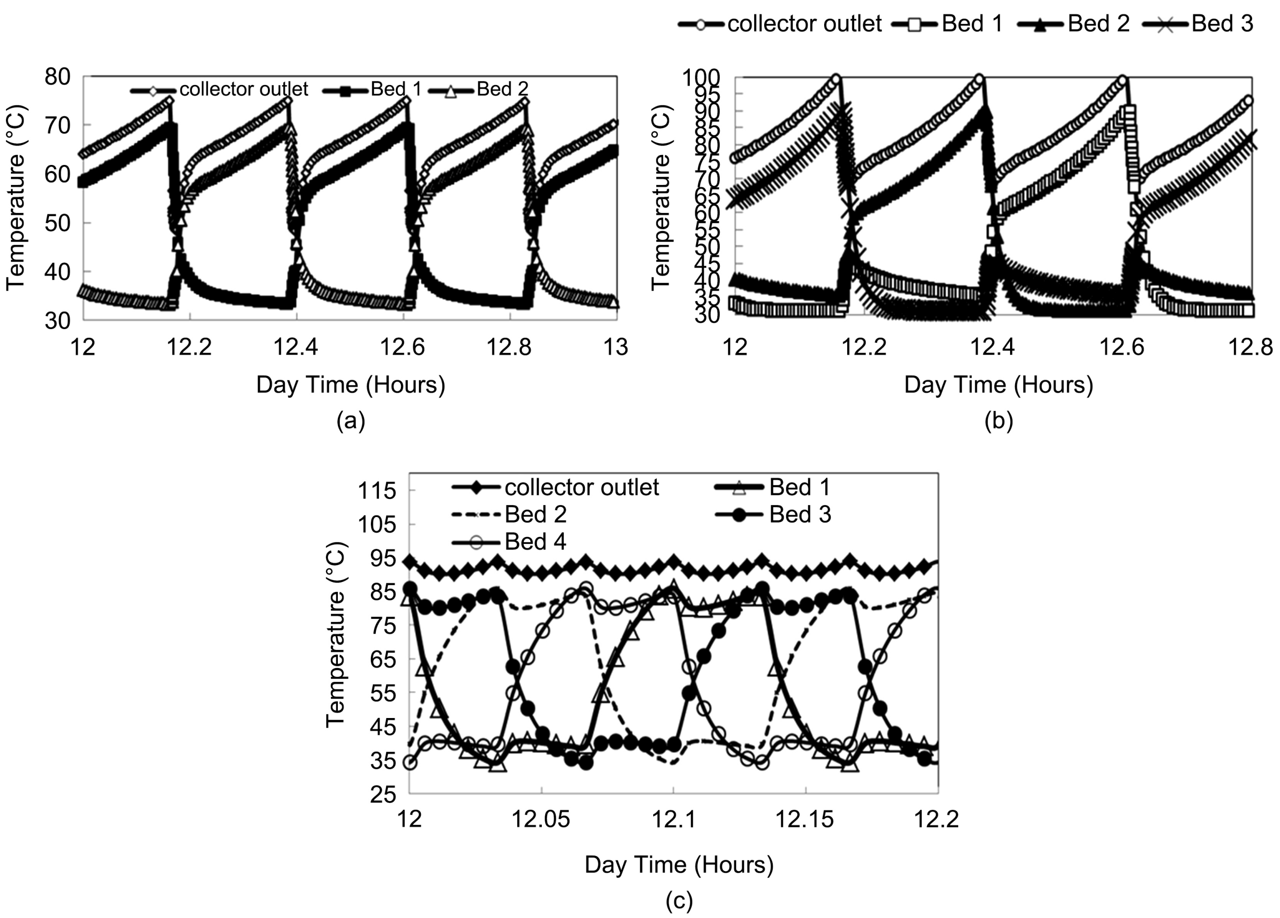

Figure 2. Temperature history of collector outlet and the adsorber beds: (a) conventional two-bed system, (b) three-bed system and (c) four-bed system.

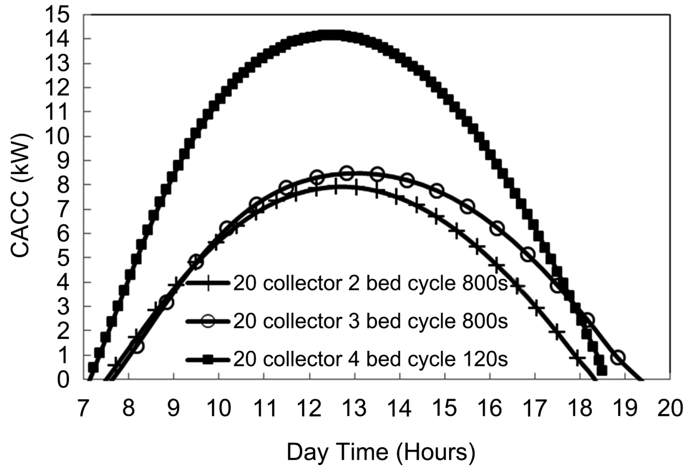

Figure 3. Comparative cyclic average cooling capacity CACC for two-bed, three-bed and four-bed systems.

Since for the three-bed and four-bed chillers the size of the containers had been reduced based on the amount of adsorbent, they need less time to heat up the bed. Therefore, a small cycle time had been chosen. On the other hand, since longer precooling time has been preferred for multiple bed systems temperature gradients is large enough to benefit the adsorption process. Hence, the system with multiple adsorbent beds with smaller cycle times is capable to produce a better cooling effect during day time as long as the solar radiation is available.

Figure 3 shows the rise of the CACC of the four-bed chiller with a small cycle time of 120s compared to that of the other chillers with a longer cycle time (800s).

5. Conclusion

The performance of a solar heat-driven four-bed adsorption chiller is compared with that of a two-bed and three-bed adsorption chiller under the same operating conditions. According to the study, it can be confirmed that solar heat has driven adsorption chillers can be made popular where low-grade heat is available by the installation of a multiple-bed reduced-sized cooling unit. Moreover, this system can utilize longer precooling time, increasing entropy of the adsorbent, and improving cooling power and COP-value.

Conflicts of Interest

The authors declare no conflicts of interest.

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