



Research Paper

Experimental investigation on composite adsorbent – Water pair for a solar-powered adsorption cooling system

L.Q. Zhu^a, C.Y. Tso^{a,b}, K.C. Chan^a, C.L. Wu^{a,c}, Christopher Y.H. Chao^{a,*}, J. Chen^c, W. He^c, S.W. Luo^c^a Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Hong Kong, China^b HKUST Jockey Club Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China^c Building Energy Research Center, Guangzhou HKUST Fok Ying Tung Research Institute, Guangzhou, China

H I G H L I G H T S

- An adsorber coated with composite adsorbents has been investigated.
- The effect of pre-heating phase on SCP and EER has been studied experimentally.
- The effect of solar collectors' area on SCP, COP and EER has been studied.
- A SCP of 208 W/kg, a COP of 0.24 and an EER of 4.5 have been achieved.
- The SCP is improved by 92.5% after conducting the pre-heating phase for 2 h.

A R T I C L E I N F O

Article history:

Received 20 October 2017

Revised 10 December 2017

Accepted 12 December 2017

Available online 13 December 2017

Keywords:

Solar-powered adsorption cooling system

Composite adsorbent

Pre-heating phase

Specific cooling power

Experimental investigation

A B S T R A C T

In this study, a solar-powered adsorption cooling system (ACS) using vehicle radiators as an adsorbent bed was built and the system performance was studied experimentally in the Guangzhou climate. 6 single-glazed flat plate solar collectors with the total area of 12 m² were utilized to collect solar energy. Zeolite 13X/CaCl₂ composite adsorbent – water was used as the adsorbent – adsorbate working pair. The composite adsorbent was coated on the fins of the vehicle radiators using an electrostatic coating method. The results show that an adsorbent coating layer with a thickness of 0.5 mm was evenly distributed, and strongly adhered. The effect of the duration of the pre-heating phase and solar collector area on the cooling performance of the ACS was investigated. A pre-heating phase of 2 h was proposed and a minimum area of solar collectors of 6 m² was recommended for a 1–2 kW scale ACS. A specific cooling power (SCP) of 208.2 W/kg of the ACS and an energy efficiency ratio (EER) of 4.5 driven by solar energy were achieved with a pre-heating phase of 2 h, and a maximum solar intensity of 880 W/m².

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Global warming and energy shortage issues have been receiving much attention in recent years all over the world. More and more electricity is being consumed, especially for air conditioning systems. Taking Hong Kong as an example, air conditioning systems driven by vapor compression refrigerant cycles account for 30–40% of a typical commercial building's electricity consumption [1]. An adsorption cooling system (ACS) is an excellent supplementary system for any size of chilled water system where space and low grade heat sources are available. ACSs can be compared to conventional vapor compression cooling systems, with the compressor

being replaced by a thermally driven adsorber. It utilizes low grade heat sources such as solar energy [2] and waste heat [3] to drive the refrigerant cycle and consumes very little electricity for the entire system [4]. Also, the adsorption/desorption cycles can be operational without the need for moving parts other than magnetic valves, thus leading to low vibration, mechanical simplicity, high reliability and a very long life time. Depending on the performance of the adsorbent, it is possible to use water as the refrigerant (the adsorbate), in contrast to the vapor compression system which uses ozone depleting refrigerants [5]. ACSs are thus more environmentally friendly [6]. As the technology becomes mature and the performance of ACSs continues to be enhanced, this will encourage building owners to adopt ACSs [7].

The adsorbent – adsorbate working pair is a key part of the ACS. Ahmed et al. [8] have summarized all available adsorbent – adsorbate working pairs and separated them into three categories, namely physical adsorbents, chemical adsorbents and composite

* Corresponding author at: Department of Mechanical and Aerospace Engineering, Main Academic Building, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China.

E-mail address: meiyhchao@ust.hk (C.Y.H. Chao).

Nomenclature

A	area, m ²
c_p	specific heat capacity of water, J/(kg K)
COP	coefficient of performance
E	electricity consumption, kWh
$\dot{m}$	mass flow rate, L/min
I	solar intensity, W/m ²
Q	power, W
SCP	specific cooling power, W/kg
T	temperature, °C
t	time, s
V	valve
W	mass, kg

Subscripts

ads	adsorption
-------	------------

av	average
$chill$	chilled water
$cool$	cooling water
des	desorption
hot	hot water
hr	heat recovery phase
in	inlet
int	initial
max	maximum
mr	mass recovery phase
out	outlet
ph	pre-heating phase
sc	solar collector
w	water

adsorbents. Solmus et al. [9] developed an ACS with an adsorbent – adsorbate working pair of natural zeolite and water and tested with a 150 °C desorption temperature. The coefficient of performance (COP) and specific cooling power (SCP) were recorded at 0.25 and 7 W/kg, respectively. Boelman et al. [10] experimentally and numerically studied a commercially available silica gel – water ACS. A COP above 0.4 were obtained with a hot water inlet temperature of 50 °C. Kayal et al. [11] experimentally investigated the adsorption characteristics of AQSOA zeolites and water for ACSs by various methods. The results showed that the adsorption capacity of AQSOA-Z02 was 0.1 g/g at the desorption temperature of 65 °C. Wang et al. [12] evaluated the ACSs from five different working pairs and found that the SCP of the silica gel – water working pair was not as high as composite adsorbent – water pairs. Tso et al. [13] developed a silica activated carbon/CaCl₂ composite adsorbent, and numerically calculated that the SCP and COP were 378 W/kg and 0.7, respectively. Chan et al. [14] developed a zeolite 13X/CaCl₂ composite adsorbent and investigated this numerically. The results showed that the difference in equilibrium water uptake between 25 and 75 °C at 870 Pa was a 0.4 g/g, which was 420% of that of zeolite 13X. However, the zeolite 13X/CaCl₂ composite adsorbent has not been investigated in a solar-powered ACS experimentally yet.

The performance of an ACS highly depends on the performance of the adsorber. Improving the method of filling adsorbent material in adsorbers is one area to be developed to enhance the COP and SCP. Wang et al. [15] experimentally investigated an ACS with fluidized-beds. Using fluidized adsorbent and fluidized-beds increased the average mass variation rate of adsorbate adsorbed or desorbed by 630% compared to the conventional fixed adsorbent beds. Sharafian et al. [16] experimentally investigated a waste heat-powered ACS using FAM-Z02 as adsorbent. The FAM-Z02 adsorbent particles were packed in between the fins of a heat exchanger which was used as the adsorbent bed. The results showed that more adsorbent packed, the poorer heat transfer ability was, which led to a lower SCP. When the amount of adsorbent was increased from 0.5 kg to 1.9 kg, the SCP of the ACS was decreased from 119.4 W/kg to 65.8 W/kg. Chan et al. [17] computational study the performance of an ACS using cylindrical shell units which was copper tubes with circular fins covered by stainless metal meshes as adsorbent beds. The silica gel adsorbent was filled in between the circular fins. A SCP of 81.4 W/kg was achieved. The performance of the integrated unit of the adsorbent material and heat exchanger (AdHex) [18], can significantly influence the adsorption capacity and heat and mass transfer, which can affect the performance of the systems [19]. Coating technology can highly enhance the performance of the AdHex [20]. Schnabel

et al. [21] studied the adsorption kinetics of zeolite coatings. The results showed that the hydrated masses of the zeolite X coatings were 1.03 g on a 5 cm × 5 cm stainless steel plate and the mass equivalent thickness was 230 μm. The heat transfer resistance between the crystal and metal layer of the zeolite X coatings was lower than that of a sample consisting of a polymer-zeolite structure glued on a metal support. Tatlier [22] developed an ACS using heat exchangers coated with zeolite and a metal-organic framework as adsorbent beds. The results showed that the power values of the metal-organic framework coatings were 4–5-fold higher than those of the zeolite coatings under the desorption temperature of 110 °C. The optimum coating thickness of metal-organic framework coatings were between 130 μm and 170 μm, and a maximum power of 80.2 kW could be achieved. Calabrese et al. [23] developed and investigated an adsorption heat pump coated with silane/SAPO 34 composite adsorbent. The adsorption capacity of the composite adsorbent coating increased by 18–19% compared to that of the pure SAPO 34 coating. Although the cooling performances of the ACSs using coating technologies was very high, the cost of using most of the coating technologies was very high. Meanwhile, although the cost of using packing methods was low, the cooling performances of the ACSs using packing methods was also low. An electrostatic coating method is a coating technology using a high voltage electrostatic electric field to force the particles charged negatively to move in the opposite direction of the electric field and coating on a plate. The cost of using this method is low, however, the performance of using this method to coat composite adsorbent on an adsorber is not well investigated yet.

In terms of application, how to use the heat sources efficiently become a key [24]. Recently, the heat sources, especially solar energy, have been investigated numerically and experimentally [25]. Saha et al. [26] experimentally investigated a double-stage, four-bed, non-regenerative solar-powered ACS. The results showed that flat plate solar collectors could effectively produce the required hot water in any tropical climate conditions. The prototype produced chilled water at 10 °C and had a cooling power of 3.2 kW with a COP of 0.36, when the desorption was 55 °C. Lu et al. [27,28] developed a heat pipe type solar-powered ACS and experimental studied its performance under typical summer weather conditions in Dezhou City. A cooling capacity and COP of 17.9 kW and 0.63 were achieved under the operating condition of a hot water inlet temperature of 79.0 °C and 65 kg adsorbent. Tso et al. [29,30] developed a numerical model to investigate the cooling performance of a solar-powered ACS. The results showed that the COP and SCP of the ACS increased significantly with the increase of the solar collector area and the ACS had the best cooling

performance with double glazed cover collectors. Koronaki et al. [31] developed a numerical model to study a solar-powered ACS using silica gel – water as working pairs in Mediterranean climate conditions. The results showed that flat plate collectors coated with chromium selective coating had a better performance than other collectors. A cooling capacity of 16 kW, and a COP of 0.51 were achieved with 47 kg adsorbent. Ambarita and Kawai [32] developed a solar-powered ACS using activated carbon – water as working pairs and experimentally investigated under Medan's climate conditions. A solar COP of 0.085, a hot generator temperature of 110.1 °C, and an evaporator temperature of 6.03 °C were achieved. However, the effect of the area of solar collectors on the cooling performance of an ACS is seldom investigated experimentally under Guangzhou's climate conditions in summer, where the weather is usually windy, hot (ambient temperature of 25–35 °C) and humid (relative humidity of 70–80%).

Optimizing the operating parameters and conditions is also a main research interest for ACSs [33]. Miyazaki et al. [34] developed a novel dual evaporator type adsorption cooling system with three adsorbent beds and tested the effect of operating temperatures and cycle time on the SCP and COP. It was found that a longer pre-heating/cooling time could reduce the temperature fluctuation of the delivered chilled water. Although the ACSs powered by solar energy have been previously studied by others numerically and experimentally, the effect of a pre-heating phase on the cooling performance of the ACSs has rarely been investigated experimentally. Besides, the effect of the duration of the pre-heating phase on the cooling performance of the ACS powered by solar energy has also not been investigated experimentally.

In our three previous studies, Tso et al. [35] developed and experimentally investigated an adsorber consisting of cylindrical shell units which were covered with metal mesh. The zeolite 13X/CaCl₂ composite adsorbent was packed between the circular fins of the cylindrical shell units. A SCP of 106 W/kg was achieved with a constant hot water inlet temperature of 85 °C. Zhu et al. [36] developed a solar-powered ACS using vehicle radiators covered by metal mesh as the adsorbent bed. Silica gel was used as the adsorbent and packed between fins. A SCP of 52.2 W/kg was achieved with conducting a pre-heating phase of 2 h. Chan et al. [37] developed and experimentally investigated an adsorber consisting of finned heat exchangers. Zeolite 13X/CaCl₂ composite adsorbent was coated on the fins of the heat exchangers. A SCP of 401 W/kg was achieved under an operating condition of a constant hot water inlet temperature of 85 °C. However, the performance of the composite adsorbent has not been investigated in an ACS driven by solar energy, which is not as stable as electrical heaters and is closer to practical application.

This study aimed at building and investigating a solar-powered ACS. In this study, the zeolite 13X/CaCl₂ composite adsorbent was coated but not packed on an adsorber, and investigated experimentally in a solar-powered ACS. The electrostatic coating method was used to coat the zeolite 13X/CaCl₂ composite adsorbent on vehicle radiators and its practicability was investigated and discussed. More importantly, the effect of the duration of the pre-heating phase and area of solar collectors on the cooling performance of the ACS was investigated experimentally under Guangzhou's climate conditions in summer.

2. Working principle and operating cycle of adsorption cooling systems

2.1. Basic working principle

The basic working principle of an ACS is that the refrigerant, which is water in this study, can continuously evaporate rapidly,

produce water vapor and produce a cooling effect in a low pressure evacuated container, named an evaporator. A large amount of adsorbent in an adsorber adsorbs the water vapor from the evaporator to maintain a low pressure condition. Cooling water is supplied to the adsorber to remove the adsorption heat. After the adsorbent is saturated with water vapor, hot water from solar collectors is supplied to the adsorber to heat up the adsorbent for performing the desorption process. In the desorption process, water vapor is desorbed from adsorbent and flows automatically from the adsorber to a condenser due to the pressure difference between the adsorber and condenser. Water vapor condenses in the condenser, and flows to the evaporator due to the pressure difference between the condenser and evaporator and the gravitational effect. The thermodynamic cycle is then completed. The two adsorbers, named adsorber A and adsorber B in this study, which are shown in Fig. 1, work alternately in order to produce the cooling effect continuously. This means that when one adsorber is in the adsorption process, the other one is in the desorption process. Between the alternating of the adsorption process and the desorption process of the adsorbers, a mass recovery and a heat recovery are proceeded. In mass recovery, two adsorbers are connected to each other and the water vapor flows from desorber to adsorber. In heat recovery, the heat transfer fluid which is water, flows through two adsorbers to recover some heat.

2.2. Pre-heating phase

In practice, a minimum desorption temperature which is about 50 °C is required for operation for the ACS [38], so that a pre-heating phase, called PH in this study, is necessary at the beginning of each day in order to increase an initial desorption temperature. The initial hot water inlet temperature was determined as the hot water inlet temperature right after the pre-heating phase and at the beginning of the ACS operated. In PH, solar collectors and the water buffer are disconnected from the ACS and the water in them is heated up by solar energy. During PH, the ACS does not operate and no cooling effect is produced.

2.3. Operating cycle

When the water in solar collectors and the water buffer is heat up to at least 50 °C at the beginning of the experiment in each day, PH stops and the ACS operates. Basically, the operating cycle of a double-bed ACS consists of two major phases, named Phase I and Phase II in this study.

In Phase I, adsorber A is in the adsorption process while adsorber B is in the desorption process. In Phase I, valves V1, V5, V6, V11, V13 and V14, which are shown in Fig. 1, are open, while the other valves are closed. Pump 1, 2 and 4 operate, while pump 3 is stopped. The water vapor evaporates in the evaporator at a low evaporation temperature and flows to adsorber A. The water vapor is adsorbed by the adsorbent in adsorber A and cooling water passing through adsorber A removes the heat generated due to the adsorption process. Adsorber B is heated to a desorption temperature by hot water passing through adsorber B from the solar collectors. The water vapor is desorbed from the adsorbent in adsorber B and flows to the condenser. The condensed water flows back to the evaporator.

Phase II is similar to Phase I, but adsorber A is heated to desorb while adsorber B is cooled to adsorb. Hence, valves V2, V4, V7, V10, V12 and V15 are opened while the other valves are closed. Pump 1, 2 and 4 operate, but pump 3 is stopped.

After Phase I, the pressure of adsorber B is much higher than that of adsorber A. A mass recovery mode, called Phase I-M, is

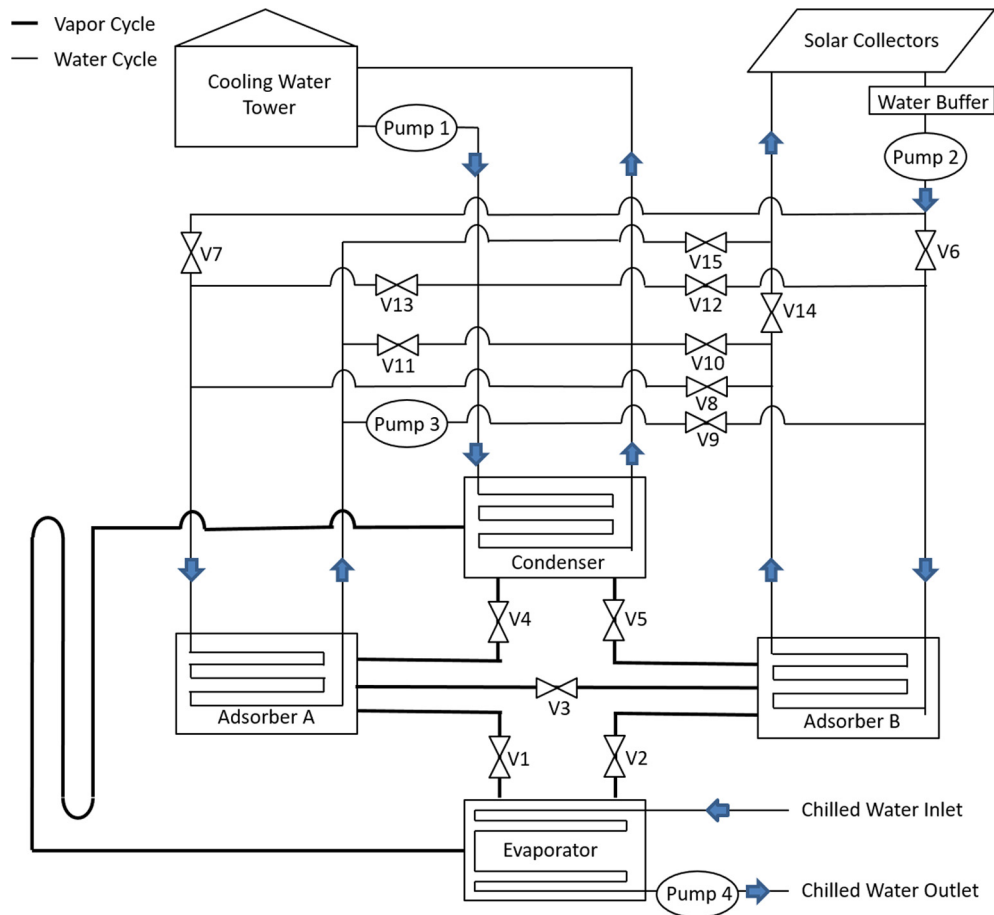


Fig. 1. Schematic diagram of the ACS.

operated. In Phase I-M, adsorber A and adsorber B are connected to each other and the water vapor flows from adsorber B to adsorber A automatically. Cooling water is supplied to adsorber A and hot water is supplied to adsorber B. The Phase I-M can further dry the heated adsorbent after Phase I. The drier adsorbent can adsorb more water vapor in Phase II. During Phase I-M, valves V3, V6, V11, V13 and V14 are open while V1-V5, V7-V10, V12, and V15 are closed. Pump 1, 2 and 4 operate, while pump 3 is stopped. Right after Phase II, another mass recovery phase, called Phase II-M, is operated. In Phase II-M, adsorber A and adsorber B are connected to each other, while hot water is continuously supplied to adsorber A and cooling water is continuously supplied to adsorber B. During Phase II-M, valves V3, V7, V10, V12 and V15 are open, and pump 1, 2 and 4 operate. Phase I-M and Phase II-M are completed after the pressure in two adsorber is balanced, and then a heat recovery phase is operated immediately, named Phase H.

In Phase H, V8, V9 are open while V1-V7 and V10-V15 are closed. Pump 3 and 4 operate while pump 1 and 2 are stopped. During Phase H, the heat transfer fluid, which is water, flows through adsorber A and B to recover about 30% of the heat input of the desorption phase via temperature difference [39,40]. Phase H is completed when the temperature of the heat transfer fluid in the two adsorbers is balanced.

In this study, a complete operating sequence of the ACS of each day can be described as: “PH → Phase I → Phase I-M → Phase H → Phase II → Phase II-M → Phase H → Phase I → ...”.

3. Description of the adsorption cooling systems

3.1. Test unit

A photograph of the ACS built in the laboratory in Nansha, Guangzhou, is shown in Fig. 2(a). The main components of the ACS located indoors were a water-cooled condenser, an evaporator, two adsorbers, and an overall controller. The condenser, evaporator, adsorbers and overall controller were located indoors, and the diameter of the indoor part of the ACS was $1\text{ m} \times 1\text{ m} \times 1.5\text{ m}$ (length $\times$ width $\times$ height). There were two components located outdoor, which were a water cooling tower shown in Fig. 2(b) and solar collectors shown in Fig. 2(c). Six 2-m^2 black chromium single-glazed flat plate solar thermal collectors with a total surface area of 12 m^2 were employed because of low cost, high absorption rate which is larger than 94%, high light transmittance of the glass which is larger than 92%. Each two solar collectors were connected in series to form a pair and 3 pairs were connected in parallel because it was easier to investigate the cooling performance of the ACS driven by various numbers of solar collectors. The solar collectors faced south with a tilt angle of 35° .

An adsorber is one of the most important elements of an ACS. A good AdHex means that it could contain more adsorbent, offer better heat and mass transfer ability and incur less frictional drag when the heat exchange fluid passes through. Because of the poor thermal conductivity of the adsorbent materials and the bulky size of the ACS, the heat and mass transfer of the AdHex should be con-

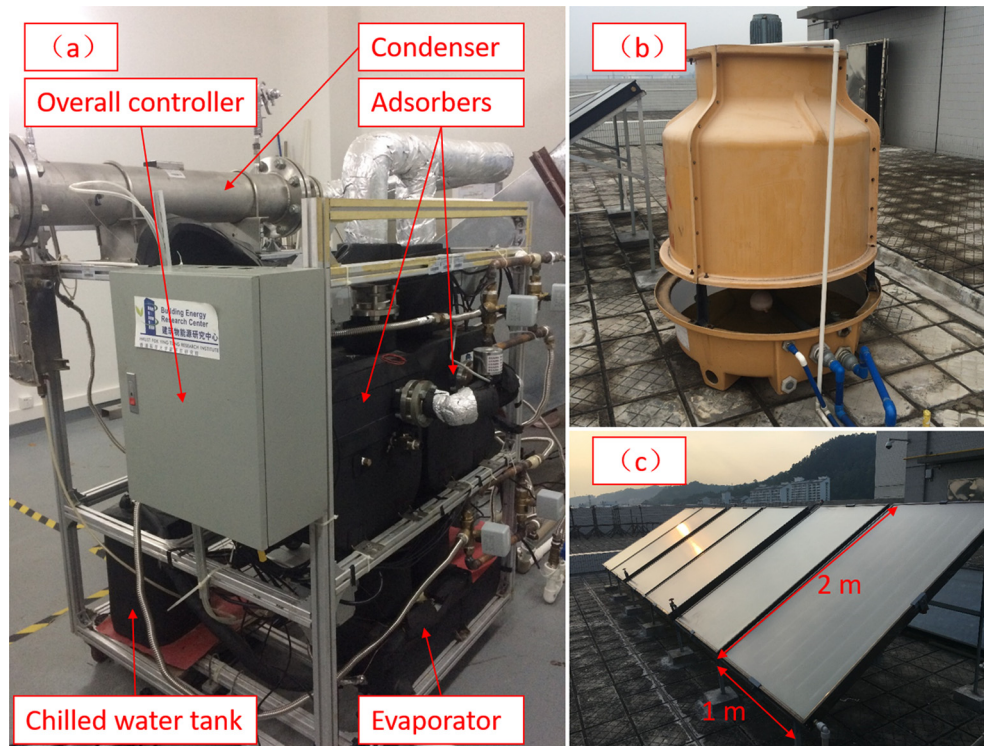


Fig. 2. (a) The ACS; (b) the water cooling tower; (c) solar collectors.

sidered carefully. In the following two sessions, the preparation of the composite adsorbents and the coated adsorbents are discussed.

3.2. Preparation of the composite adsorbent

The raw materials used to prepare the composite adsorbent were zeolite 13X powder with an average particle size of $2\ \mu\text{m}$ and anhydrous CaCl_2 powder with a concentration of 96 wt%. The composite adsorbent was prepared using the method developed by Chan et al. [14], and the steps are shown as follows:

- (1) Dry the zeolite 13X at $200\ ^\circ\text{C}$ for 12 h for ion exchange and calcination;
- (2) Mix the dried zeolite 13X with aqueous CaCl_2 solution with a concentration of 40 wt% in the mass ratio of 1:9, stirring at room temperature for 24 h. During the synthesis process of the composite adsorbent, ion-exchange is first conducted between zeolite 13X and Ca^{2+} ion in an aqueous solution. CaCl_2 salt is then impregnated into zeolite 13X particles by immersing the zeolite 13X in a concentrated CaCl_2 aqueous solution. The solution can fill up all the pores, including the micro-pores, of the zeolite;
- (3) Filter the CaCl_2 solution and wash the Ca-ion-exchanged zeolite with deionized water;
- (4) Dry the Ca-ion-exchanged zeolite at $110\ ^\circ\text{C}$ for 12 h. After drying, the salt is confined into the porous solid matrix. The composite adsorbent is formed, and this changes the properties of the composite adsorbent and affects its performance.

3.3. Preparation of the coated adsorbents

In order to provide a better heat transfer performance, a vehicle radiator with fins was one of the choices selected as the adsorbent bed because of its low cost, fast assembly, and its ease in further manufacturing. However, if the adsorbent particles

were packed loosely in between the fins of the vehicle radiator, the contact area between the adsorbent and fins was far smaller than the total area of fins resulting in a high thermal contact resistance, which means that the heat transfer capability was reduced. What's more, the adsorbent particles were packed will block some of the airway, which led to a lower mass transfer. In order to enhance the heat and mass transfer of the AdHex, coating method was used to coat the adsorbent on the surface of the fins of the vehicle radiators. Coating adsorbent directly on the surface of fins of the vehicle radiators can enhance the contact area and reduce the thermal contact resistance between the adsorbent and vehicle radiators.

Electrostatic coating is a coating method using a high voltage electrostatic electric field to force the particles of the mixture of the adsorbent and epoxy polyester charged negatively to move in the opposite direction of the electric field and coating the particles on the fins of the vehicle radiators [41]. The preparation of the electrostatic coating on the vehicle radiators is shown as follows:

- (1) Surface oil removal and passivation for the vehicle radiator;
- (2) Dry the adsorbent at a temperature of $150\ ^\circ\text{C}$ for 24 h, mix the dry adsorbent and epoxy polyester with a mixing ratio of 4:1, powder it and then put the powder into a canister of the electrostatic sprayer which is shown in Fig. 3(a);
- (3) Spray the powder in the canister through the spray gun due to the pressure different created by a pressure pump. The distance between the spray gun and vehicle radiator is 20 cm and the spray direction is 90° with the vehicle radiator;
- (4) Heat up the coated vehicle radiator to $150\ ^\circ\text{C}$ for 24 h to solidify the adsorbent on the fins of the vehicle radiator.

Fig. 3(b) and (c) show photographs of a heat exchanger coated with adsorbent material and a raw heat exchanger. The electrostatic coating has the following advantages:

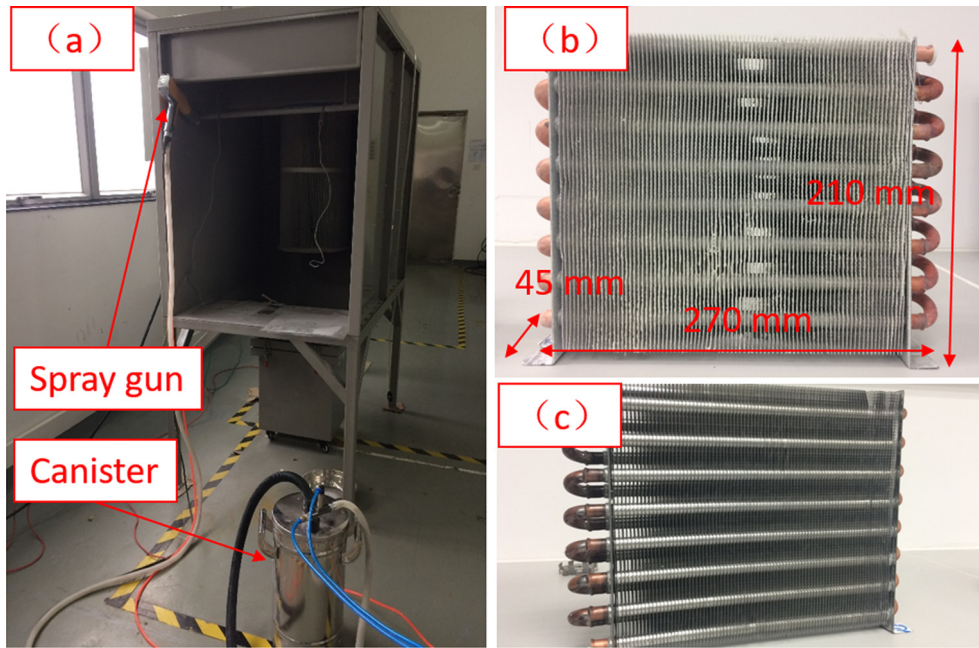


Fig. 3. (a) An electrostatic sprayer; (b) a vehicle radiator coated with adsorbent material; (c) a raw vehicle radiator.

- (1) The adsorbent particles can be shot to every part of the fins because of the combination of mechanical and electrical forces, so that the adsorbent coating is evenly distributed [42];
- (2) The epoxy polyester was used as the binder, so the adsorbent particles were strongly adhered on the fins and not easy to drop off [43];
- (3) When the thickness of the adsorbent coating is larger than 1 mm, the thermal resistance will increase and limit the cooling performance of the ACS because of the low conductivity of adsorbents [44]. Utilizing electrostatic coating, the thickness, which can be as low as 10 μm [45], is smaller than that utilizing dip coating method and fulfill the requirement.
- (4) The coating particles on the surfaces can be well-confined and the thickness of the coating can be well-controlled [45].
- (5) The high voltage electrostatic electric field does not affect the properties of the powder passing through the spray gun [41]. The solidified binder does not affect the adsorption capacity of the composite adsorbent and is not volatile [43].
- (6) The preparation of the adsorber using electrostatic coating is fast and low cost.

The size of the heat exchangers used was 270 mm $\times$ 210 mm $\times$ 45 mm. The fins were made of aluminum, and the average thickness of the coating was 0.5 mm, which was measured with a micrometer. 700 g of composite adsorbent was coated on a vehicle radiator and 8 vehicle radiators connected in parallel were installed in an adsorber, so that totally 5.6 kg adsorbent was used in an adsorber. The composite adsorbent consisted of zeolite 13X and CaCl_2 , which is corrosive when oxygen exists. However, the heat exchangers were taken out from the adsorbers after completing all experiments, and no corrosion problem was found. This was because that the ACSs operated under a low-pressure condition, so that there was almost no oxygen inside the adsorbers.

3.4. Control system

A constant temperature water bath with a cooling power of 2 kW was used to generate the controllable and constant temperature chilled water to the ACS. A 2 kW electric immersion heater

was inserted into the water cooling tower in order to control the cooling water inlet temperature. The electric immersion heater was controlled by a PID temperature controller with on/off control method. All the K-type thermocouples with data acquisition devices were used to record temperatures of the system components. Three vortex flowmeters with data acquisition devices were used to record the hot water flow rate, cooling water flow rate and chilled water flow rate. NI LabVIEW software was used to build a virtual data acquisition device program to show the data on the screen of the computer and store them on the computer's hard disk every 3 s. The solar intensity was measured by a TES solar power meter. The control of the valves was implemented through software programming. Single step control and independent control of the pump through a wireless remote control module were used. The electricity consumption was estimated by an electricity meter.

3.5. Calculations

Eq. (1) is used to calculate the average SCP of an experiment in a day of the ACS:

$$\text{SCP} = \frac{\int_0^t Q_{\text{chill}} dt}{Wt}, \quad (1)$$

where Q_{chill} represents the cooling output power; t represents the total operation time for the ACS in a day; W represents the weight of the composite adsorbent in the adsorber. The cooling output power is calculated from Eq. (2) below:

$$Q_{\text{chill}} = \dot{m}_{\text{chill}} c_{p,w} (T_{\text{chill,in}} - T_{\text{chill,out}}), \quad (2)$$

where $\dot{m}_{\text{chill}}$ represents the mass flow rates of the chilled water; $c_{p,w}$ represents the isobaric specific heat capacity of water; $T_{\text{chill,in}}$ and $T_{\text{chill,out}}$ represent chilled water inlet and outlet temperatures to the evaporator. The average energy efficiency ratio (EER) is calculated from the Eq. (3):

$$\text{EER} = \frac{\int_0^t Q_{\text{chill}} dt}{E}, \quad (3)$$

where E represents the electricity consumption which includes the electricity consumption of pumps, valves, and control system and

measured by an electricity meter. The average COP is calculated from the Eq. (4):

$$\text{COP} = \frac{\int_0^t Q_{\text{chill}} dt}{\int_0^t Q_{\text{hot}} dt}, \quad (4)$$

where Q_{hot} represents the thermal input power and is calculated from the Eq. (5):

$$Q_{\text{hot}} = \dot{m}_{\text{hot}} c_{p,w} (T_{\text{hot,in}} - T_{\text{hot,out}}), \quad (5)$$

where $\dot{m}_{\text{hot}}$ represents the hot water mass flow rate; $T_{\text{hot,in}}$, and $T_{\text{hot,out}}$ represent hot water inlet and outlet temperatures from the solar collectors to the adsorber. Moreover, since the temperature of the composite adsorbent is hard to measure, $T_{\text{hot,in}}$ is regarded as the desorption temperature. Since the thermal input power was obtained from the temperature difference between the inlet and outlet from the solar collectors to the adsorber, the heat loss from the ACS to the ambient environment and the heat loss on the metallic adsorbers including the chassis, heat exchangers, pipes and heat transfer fluid on the COP were included in the calculation. It should be noticed that the heat loss from the solar collectors to the ambient environment was not included in this calculation. Most of the heat loss was from the adsorbers, the piping system through which heat transfer fluid circulates, and the heat capacities of the metal and heat transfer fluid.

3.6. Error analysis

The K-type thermocouples have an uncertainty of ± 0.1 °C. The vortex flowmeters have an uncertainty of $\pm 0.5\%$. The solar power meter has an uncertainty of ± 10 W/m². The electricity meter has an uncertainty of 0.1 kWh. According the uncertainties and the equations listed above, the SCP, EER and COP have uncertainties of $\pm 8.6\%$, $\pm 8.9\%$ and $\pm 17.3\%$, respectively.

4. Results and discussion

The operating condition is shown in Table 1. In Table 1, $T_{\text{cool,in}}$ represents the cooling water inlet temperature to the adsorber; t_{ph} represents the pre-heating phase time; $t_{\text{ads,des}}$ represents the adsorption/desorption phase time; t_{mr} represents the mass recovery time; t_{hr} represents the heat recovery phase time; and $\dot{m}_{\text{cool}}$ represents the adsorber cooling water mass flow rate. The hot water inlet temperature depended on the area of the solar collectors and solar intensity. The cooling water inlet temperature and chilled water inlet temperature were controlled at around 25 °C and 16 °C, respectively. In the previous study [35], various operating conditions were investigated and optimized. In this study, the operating conditions of the ACS were set according the previous study as shown in the following table.

Table 1
Operating conditions of the ACS.

Parameters	Values	Unit
$T_{\text{cool,in}}$	25	°C
$T_{\text{chill,in}}$	16	°C
$t_{\text{ads,des}}$	660	s
t_{mr}	85	s
t_{hr}	50	s
$\dot{m}_{\text{hot}}$	30	L/min
$\dot{m}_{\text{cool}}$	30	L/min
$\dot{m}_{\text{chill}}$	8	L/min

4.1. The effect of the duration of the pre-heating phase on the cooling performance of the ACS

Fig. 4 shows the EER and average SCP of the ACS conducting various duration of pre-heating phase. The pre-heating phase started at 8:00 and the whole experiment ended at 18:00. In this study, 0 min, 30 min, 60 min, 90 min, 120 min and 150 min were selected as the duration of the pre-heating phase. From Fig. 4, it was found that the average SCP reached the peak when the duration of the pre-heating phase was 120 min. As illustrated in Fig. 4, compared to the SCP of the experiment conducted on 1 August 2017, which had no pre-heating phase, the SCP of the experiment conducted on 15 August, which had a 2-h pre-heating phase, improved by 92.5%. With the increase of the cooling power, the EER increased relatively. The reason was that the electricity consumption of the ACS was the same when it was operating.

The experiments were conducted on different days, and the solar intensity and hot water inlet temperature profiles are shown in Fig. 5. In the pre-heating phase, the hot water inlet temperature increased rapidly. As shown in Fig. 4, the longer the duration of the pre-heating phase, the higher the hot water inlet temperature achieved, the larger the SCP achieved after the system operated. However, there was no cooling effect during the pre-heating phase, so that the average SCP might decrease when the duration of the pre-heating phase was too long. In Fig. 5, it is shown that the absorbed solar intensity on solar collector surface decreased rapidly after 15:00, which led to the decrease of hot water inlet temperature and a reduction of the cooling effect. The reason for this was that the location and tilt angle of the solar collectors were fixed and the solar collectors could not receive direct sunlight. For example, the actual solar intensity at around 17:00 was about 400–500 W/m², while only 100–200 W/m² could be absorbed by the solar collectors.

In Table 2, I_{av} , I_{max} , $T_{\text{hot,in,int}}$, $T_{\text{hot,in,av}}$, and $T_{\text{hot,in,max}}$ are shown. I_{av} , I_{max} , $T_{\text{hot,in,int}}$, $T_{\text{hot,in,av}}$, and $T_{\text{hot,in,max}}$ represent the average solar intensity, maximum solar intensity, initial hot water inlet temperature, average hot water inlet temperature and maximum hot water inlet temperature. According to Table 2, the longer the duration of the pre-heating phase was, the higher the initial hot water inlet temperature, average hot water inlet temperature and maximum hot water inlet temperature were achieved. Meanwhile, it was found that the solar intensity in days tested was similar so that the results of the effect of duration of the pre-heating phase on the cooling performance was comparable.

4.2. The effect of the area of the solar collectors on the cooling performance of the ACS

Table 3 indicates the average and maximum solar intensity and hot water outlet temperature in different days for the experiments on the area of solar collectors, A_{sc} . These experiments were operated under the same operating conditions as shown in Table 1. It should be noticed that a pre-heating phase of 2 h was conducted in these experiments. The larger the area of solar collectors is, the more solar energy is absorbed, the higher the average hot water inlet temperature is and the higher the average SCP achieved. When the area of solar collectors was controlled at 4 m², the maximum hot water inlet temperature and average hot water inlet temperature were only 53.1 °C and 44.3 °C, which led to a low cooling performance. With the reduction of the area of solar collectors from 12 m² to 4 m², the EER decreased from 4.5 to 1.6. The flow resistance decreased with the reduction of the area of solar collectors, which led to the reduction of the electricity consumption of the pump 2. However, the total electricity consumption of the ACS was almost unchanged because the electricity

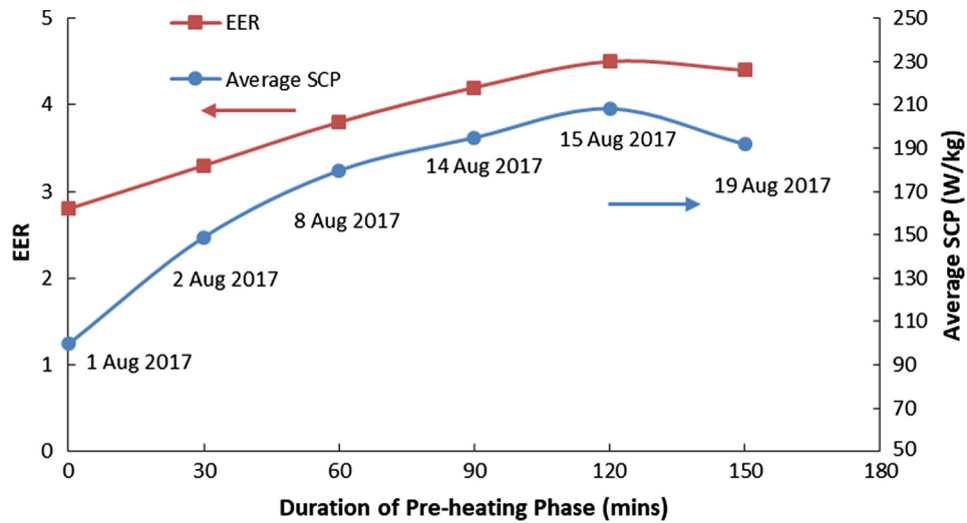


Fig. 4. The effect of duration of the pre-heating phase on the EER and average SCP of the ACS.

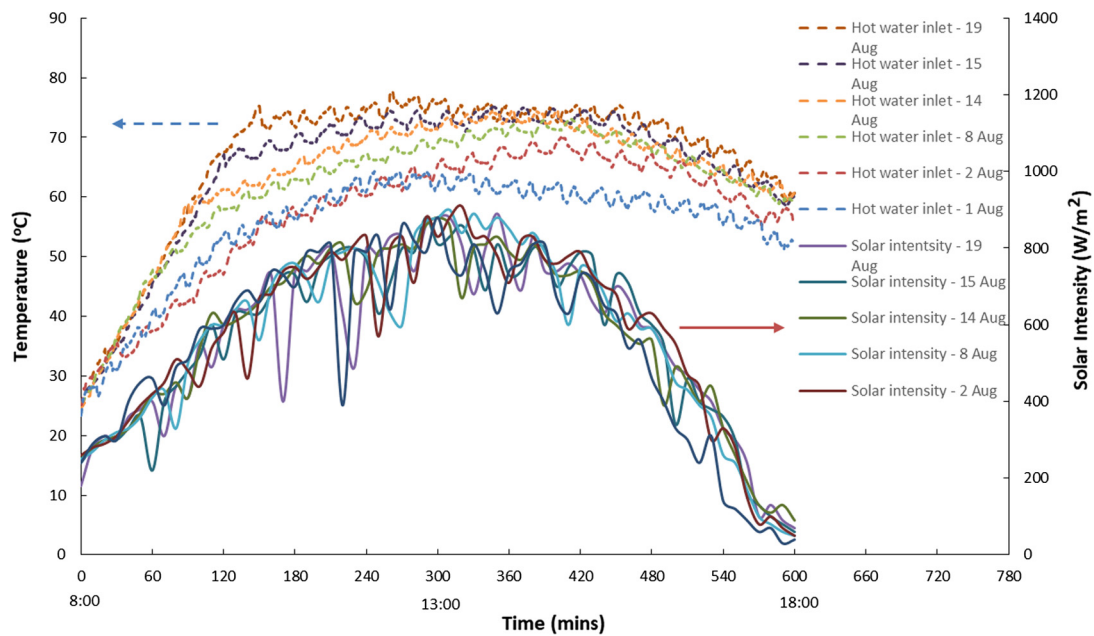


Fig. 5. Solar intensity and hot water inlet temperature profiles in different days.

Table 2

Solar intensity and hot water inlet temperature on different days for the experiments on the duration of pre-heating phase.

Date	I_{av} (W/m ²)	I_{max} (W/m ²)	$T_{hot,in,int}$ (°C)	$T_{hot,in,av}$ (°C)	$T_{hot,in,max}$ (°C)
1 Aug 2017	550	880	23.3	55.2	64.2
2 Aug 2017	580	910	35.5	57.4	70.0
8 Aug 2017	570	900	47.8	62.0	73.1
14 Aug 2017	580	880	59.2	63.7	74.3
15 Aug 2017	570	880	67.2	65.1	75.3
19 Aug 2017	570	890	75.3	67.1	76.8

Table 3

Solar intensity and hot water inlet temperature in different days for the experiments on the area of solar collectors.

A_{sc} (m ²)	Date	I_{av} (W/m ²)	I_{max} (W/m ²)	$T_{hot,in,av}$ (°C)	$T_{hot,in,max}$ (°C)	SCP (W/kg)	EER	COP
12	15 Aug 2017	570	880	65.1	75.3	208.2	4.5	0.24
8	4 Sept, 2017	550	880	56.1	67.3	117.9	3.1	0.2
4	8 Sept, 2017	550	860	44.3	53.1	41.1	1.6	0.13

consumption for other pumps, valves, and control system remained the same. Therefore, the EER highly depends on the cooling power of the ACS, which is dependent on the hot water inlet temperature. In the experiment conducted on 15 August, as the average hot water inlet temperature was 65.1 °C, limiting the cooling power of the ACS, the EER was only 4.5. The reduction of the area of solar collectors led to the reduction of cooling power, and it also led to the reduction of the EER. On the other hand, increasing the solar collector area is one of the ways to increase the hot water inlet temperature, so that the EER can be enhanced. Similar to the SCP and EER, the COP increased from 0.13 to 0.24 with the increase of the area of the solar collectors. The cooling capacity increased with the increase of the area of the solar collectors, while the heat loss did not increase as much as the cooling capacity, which led to the increase of the COP. Based on Table 3, average hot water inlet temperatures of 44.3 °C and 56.1 °C were achieved in the experiments utilizing the solar collectors with areas of 4 m² and 8 m², respectively. It was extrapolated that 6 m² is the smallest solar collector area for this ACS to operate since the hot water inlet temperature can achieve 50 °C.

4.3. A real-time temperature profiles of the heat transfer fluid and pressure profiles of two adsorbers

Fig. 6 shows the temperature profiles of the heat transfer fluid in the experiment conducted on 15 August. The hot water inlet temperature increased by 42 °C in pre-heating process and an initial hot water inlet temperature of 65.1 °C was achieved at the beginning of the ACS operated, which was 10:00. The temperature then slightly decreased to about 63 °C since hot water was supplied to the desorber to perform the desorption process. This temperature reduction depended on the volume of water in desorber and pipes (~0.016 m³) and that in the solar collectors and water buffer (~0.146 m³). A larger water buffer leads to a smaller temperature reduction. At first 3 h after the ACS operated (10:00–13:00), the hot water inlet temperature increased slowly, because the solar energy absorbed was slightly larger than the energy consumed in the desorption process. The hot water inlet temperature increased to 75.3 °C at about 13:00, after that it stayed almost constant till 15:00. The hot water inlet temperature started to decrease slowly after 15:00 due to the reduction in solar intensity.

Fig. 7 shows the pressure profiles of two adsorbers in the experiment conducted on 15 August. During the pre-heating phase, the pressures in the two adsorbers were almost unchanged since the ACS was not operated. Right after the pre-heating phase, the ACS operated (i.e. adsorber A adsorbed and adsorber B desorbed). The pressure in adsorber A increased slightly since the pressure in the evaporator was higher than that in adsorber A initially. After the cooling water was supplied to adsorber A, the adsorption process started, so that the pressure in adsorber A could be maintained at a low pressure level (e.g. 1300 Pa). The pressure in adsorber B increased significantly because of the desorption process. After the pressure in adsorber B reached the peak (e.g. 8000 Pa), it started to decrease since the water vapor was condensed in the condenser. The maximum value of the pressure in the desorber increased with the increase in the hot water inlet temperature since more water vapor could be desorbed at a higher hot water inlet temperature, meanwhile, the minimum value of the pressure in the adsorber decreased because more water vapor could be adsorbed with a drier adsorbent.

In Table 4, some of the cooling performances obtained by different ACSs were shown. The results should not be compared to one another, because they were obtained with different ACSs, under different working conditions, especially weather conditions and solar intensity. The results should be used as a reference of what can be expected from the solar-powered ACSs. In our first previous study [35], zeolite 13X/CaCl₂ composite adsorbent was utilized as well as in this study. It is found that the SCP of this study increased by 96.4% compared to our first previous study, even though the hot water inlet temperature of our previous study was higher than that of this study. This shows that the cooling performance of the ACS has been improved significantly utilizing the electrostatic coating method instead of the packing method. In our second previous study [36], although the maximum solar intensity (910 W/m²) and that of this study (880 W/m²) was similar, the SCP of this study was four times larger than that of our second previous study. This shows that utilizing zeolite 13X/CaCl₂ composite adsorbent can significantly enhance the cooling performance of the ACS. In our third previous study [37], the SCP was 92.6% higher than that of this study. However, the composite adsorbent was investigated under a constant hot water temperature of 85 °C supplied by electrical heaters. This does not represent the full picture of the perfor-

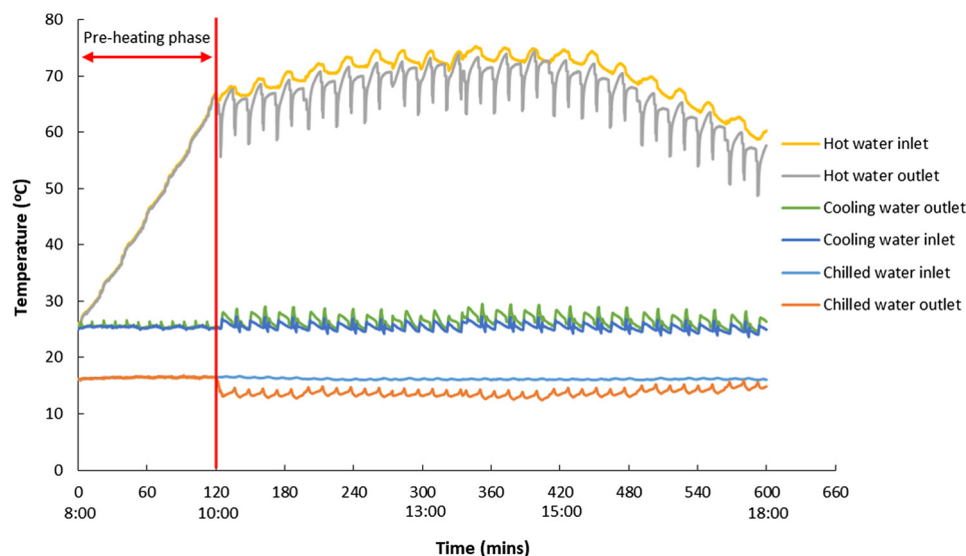


Fig. 6. A real-time temperature profiles of the heat transfer fluid.

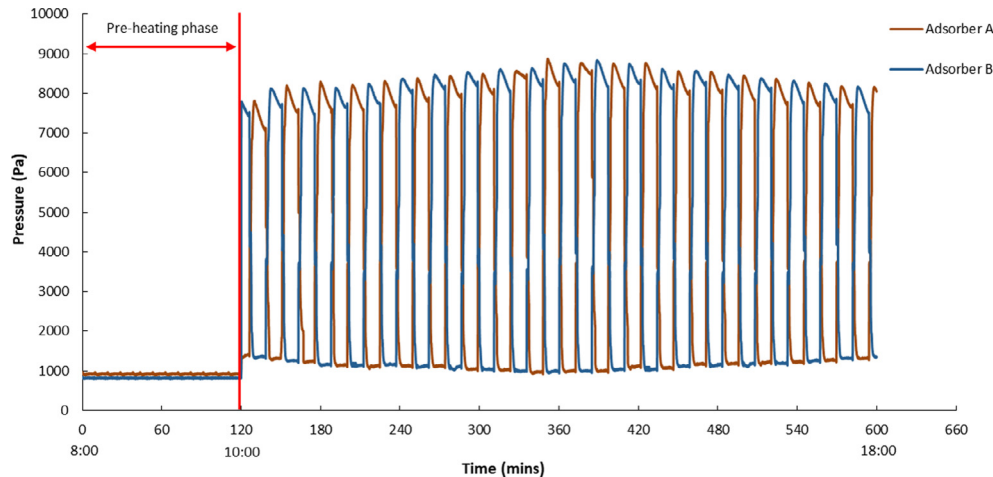


Fig. 7. A real-time pressure profiles of two adsorbers.

Table 4

A list of this study and other similar studies.

	Adsorbent-adsorbate working pair	Adsorbent filling method	Maximum solar intensity or daily insolation	SCP or ice production	COP
Allouhi's study [46]	Activated carbon-methanol	Packing in beds	1100 W/m ²	3.18 W/kg	0.13
Anyanwu's study [47]	Activated carbon-methanol	Packing between inner and outer tubes	1000 W/m ²	31.76 kJ/kg/day	0.09
Deshmukh's study [48]	Silica gel-water	N.A.	31.12 kWh/day	337.5 kJ/kg/day	0.63
El-Fadar's study [49]	Activated carbon-ammonia	Packing around tubes	880 W/m ²	2411 kJ/kg/day	0.26
Khattab's study [50]	Domestic charcoal-methanol	Packing in beds	680 W/m ²	15.67 kg/kg/m ² /day	0.16
Li's study [51]	CaCl ₂ /activated carbon-ammonia	Packing around tubes	3 kWh/m ² /day	1.67 kg/kg/day	0.15
Zhang's study [52]	Activated carbon-methanol	Packing in beds	700 W/m ²	17.6 W/kg	0.34
Previous Study 1 [35]	Zeolite 13X/CaCl ₂ -water	Packing between fins	N.A.	106.0 W/kg	0.16
Previous Study 2 [36]	Silica gel-water	Packing between fins	840 W/m ²	52.2 W/kg	0.29
Previous Study 3 [37]	Zeolite 13X/CaCl ₂ -water	Coating on fins	N.A.	401.0 W/kg	0.3
This study	Zeolite 13X/CaCl ₂ -water	Coating on fins	880 W/m ²	208.2 W/kg	0.24

mance of the composite adsorbent, especially its performance in real application.

5. Conclusions

In this study, a double-bed ACS was built. 8 vehicle radiators were assembled as an adsorbent bed and a total of 5.6 kg of zeolite 13X/CaCl₂ composite adsorbents were coated using electrostatic coating method in the adsorber. The effects of the duration of pre-heating phase, the area of solar collectors and the electrostatic coating method on the SCP of the ACS were experimentally investigated. The following conclusions are drawn.

- (1) Compared to the SCP of the ACS without conducting the pre-heating phase, the average SCP of the ACS with conducting the pre-heating phase improved significantly (e.g., an average SCP of 208.2 W/kg, an EER of 4.5 were achieved and an improvement of 92.5% and 60.7% were recorded respectively with conducting the pre-heating phase of 2 h). However, the average SCP decreases if the duration of the pre-heating phase is too long because there is no cooling effect during the pre-heating phase.
- (2) The larger the area of solar collectors, the higher the average SCP achieved. Utilizing at least 3 solar collectors with total area of 6 m² is recommended for this 1–2 kW scale solar-powered ACS.
- (3) Compared with our previous studies, the results of this study and our third previous study show that the adsorbers coated with zeolite 13X/CaCl₂ composite adsorbent using the coat-

ing method improve the cooling performance of the solar-powered ACS significantly. Both the electrostatic coating method and the zeolite 13X/CaCl₂ composite adsorbent have a good potential on utilizing in solar-powered ACSs.

Acknowledgement

Funding sources for this research are provided by the Hong Kong Research Grant Council via General Research Fund accounts 16201114, and the HKUST Initiation Grant via the account code of IGN16EG05.

References

- [1] E.M.S.D., Hong Kong Energy End-use Data. Electrical & Mechanical Services Department HKSAR, 2015.
- [2] H. Nidal, A. Hamdeh, M.A. Al-Muhtaseb, Optimization of solar adsorption refrigeration system using experimental and statistical techniques, *Energy Convers. Manag.* 51 (2010) 1610–1615.
- [3] K.C. Ng, K. Thu, B.B. Saha, A. Chakraborty, Study on a waste heat-driven adsorption cooling cum desalination cycle, *Int. J. Refrig.* 35 (2012) 685–693.
- [4] K.R. Ullah, R. Saiur, H.W. Ping, R.K. Akikur, N.H. Shuvo, A review of solar thermal refrigeration and cooling methods, *Renew. Sust. Energy Rev.* 24 (2013) 499–513.
- [5] R.Z. Wang, Adsorption refrigeration research in Shanghai Jiao Tong University, *Renew. Sust. Energy Rev.* 5 (2001) 1–37.
- [6] E.E. Anyanwu, Review of solid adsorption solar refrigeration II: an overview of the principles and theory, *Energy Convers. Manag.* 45 (2004) 1279–1295.
- [7] B.B. Saha, S. Koyama, T. Kashiwagi, A. Akisawa, K.C. Ng, H.T. Chua, Waste heat driven dual-mode, multi-stage, multi-bed regenerative adsorption system, *Int. J. Refrig.* 26 (2003) 749–757.
- [8] A. Ahmed, M. Salem, I.M. Ismael, A.H.H. Ali, M.G. Morsy, B.B. Saha, An overview on adsorption pairs for cooling, *Renew. Sust. Energy Rev.* 19 (2012) 565–572.

- [9] I. Solmus, B. Kaftanoglu, C. Yamali, D. Baker, Experimental investigation of a natural zeolite-water adsorption cooling unit, *Appl. Energy* 88 (2011) 4206–4213.
- [10] E.C. Boelman, B.B. Saha, T. Kashiwagi, Experimental investigation of a silica gel – water adsorption refrigeration cycle – the influence of operating conditions on cooling output and COP, *ASHRAE Trans. Res.* 101 (1995) 358–366.
- [11] S. Kayal, S. Baichuan, B.B. Saha, Adsorption characteristics of AQSOA zeolites and water for adsorption chillers, *Int. J. Heat Mass Transf.* 92 (2016) 1120–1127.
- [12] D.C. Wang, Y.H. Li, D. Li, Y.Z. Xia, J.P. Zhang, A review on adsorption refrigeration technology and adsorption deterioration in physical adsorption systems, *Renew. Sust. Energy Rev.* 14 (2009) 344–353.
- [13] C.Y. Tso, C.Y.H. Chao, Activated carbon, silica-gel and calcium chloride composite adsorbents for energy efficient solar adsorption cooling and dehumidification systems, *Int. J. Refrig.* 35 (2012) 1626–1638.
- [14] K.C. Chan, C.Y.H. Chao, G.N. Sze-To, K.S. Hui, Performance predictions for a new zeolite 13X/CaCl₂ composite adsorbent for adsorption cooling systems, *Int. J. Heat Mass Transf.* 55 (2012) 3214–3224.
- [15] Q. Wang, X. Gao, J.Y. Xu, A.S. Maiga, G.M. Chen, Experimental investigation on a fluidized-bed adsorber/desorber for the adsorption refrigeration system, *Int. J. Refrig.* 35 (2012) 694–700.
- [16] A. Sharaifan, S.M.N. Mehr, P.C. Thimmaiah, W. Huttema, M. Bahrami, Effects of adsorbent mass and number of adsorber beds on the performance of a waste heat-driven adsorption cooling system for vehicle air conditioning applications, *Energy* 12 (2016) 481–493.
- [17] K.C. Chan, C.Y. Tso, C.Y.H. Chao, C.L. Wu, Experiment verified simulation study of the operating sequences on the performance of adsorption cooling system, *Build. Simul.* 8 (3) (2015) 255–269.
- [18] Y.I. Aristov, I.S. Glaznev, I.S. Gernik, Optimization of adsorption dynamics in adsorptive chillers: loose grains configuration, *Energy* 46 (1) (2012) 484–492.
- [19] A. Frazzica, G. Fuldner, A. Sapienza, A. Freni, L. Schnabel, Experimental and theoretical analysis of the kinetic performance of an adsorbent coating composition for use in adsorption chillers and heat pumps, *Appl. Therm. Eng.* 73 (2014) 1022–1031.
- [20] X.H. Li, X.H. Hou, X. Zhang, Z.X. Yuan, A review on development of adsorption cooling–novel beds and advanced cycles, *Energy Convers. Manag.* 94 (2015) 221–232.
- [21] L. Schnabel, M. Tatlier, F. Schmidt, A. Erdem-Senatalar, Adsorption kinetics of zeolite coatings directly crystallized on metal supports for heat pump applications (adsorption kinetics of zeolite coatings), *Appl. Therm. Eng.* 30 (2010) 1409–1416.
- [22] M. Tatlier, Performances of MOF vs. zeolite coatings in adsorption cooling applications, *Appl. Therm. Eng.* 113 (2017) 290–297.
- [23] L. Calabrese, V. Brancato, L. Bonaccorsi, A. Frazzica, A. Capri, A. Freni, E. Proverbio, Development and characterization of silane-zeolite adsorbent coatings for adsorption heat pump applications, *Appl. Therm. Eng.* 116 (2017) 364–371.
- [24] H.Z. Hassan, A.A. Mohamad, H.A. Al-Ansary, Development of a continuously operating solar-driven adsorption cooling system: thermodynamic analysis and parametric study, *Appl. Therm. Eng.* 48 (2012) 332–341.
- [25] R.Z. Wang, R.G. Oliveira, Adsorption refrigeration – an efficient way to make good use of waste heat and solar energy, *Prog. Energy Combust. Sci.* 32 (2006) 424–458.
- [26] B.B. Saha, A. Akisawa, T. Kashiwagi, Solar/waste heat driven two-stage adsorption chiller: the prototype, *Renew. Energy* 23 (2001) 93–101.
- [27] Z.S. Lu, L.W. Wang, R.Z. Wang, Experimental analysis of an adsorption refrigerator with mass and heat-pipe heat recovery process, *Energy Convers. Manag.* 53 (2012) 291–297.
- [28] Z.S. Lu, R.Z. Wang, Z.Z. Xia, Experimental analysis of an adsorption air conditioning with micro-porous silica gel-water, *Appl. Therm. Eng.* 50 (2013) 1015–1020.
- [29] C.Y. Tso, S.C. Fu, C.Y.H. Chao, Modeling a solar-powered double bed novel composite adsorbent (silica activated carbon/CaCl₂) – water adsorption chiller, *Build. Simul.* 7 (2014) 185–196.
- [30] C.Y. Tso, C.Y.H. Chao, S.C. Fu, Performance analysis of a waste heat driven activated carbon based composite adsorbent – water adsorption chiller using simulation model, *Int. J. Heat Mass Transf.* 55 (2012) 7596–7610.
- [31] I.P. Koronaki, E.G. Papoutsis, V.D. Papaefthimiou, Thermodynamic modeling and exergy analysis of a solar adsorption cooling system with cooling tower in mediterranean conditions, *Appl. Therm. Eng.* 99 (2016) 1027–1038.
- [32] H. Ambarita, H. Kawai, Experimental study on solar-powered adsorption refrigeration cycle with activated alumina and activated carbon as adsorbent, *Case Studies Therm. Eng.* 7 (2016) 36–46.
- [33] A. Sapienza, S. Santamaria, A. Frazzica, A. Freni, Influence of the management strategy and operating conditions on the performance of an adsorption chiller, *Energy* 36 (2011) 5532–5538.
- [34] T. Miyazaki, A. Akisawa, B.B. Saha, The performance analysis of a novel dual evaporator type three-bed adsorption chiller, *Int. J. Refrig.* 33 (2010) 276–285.
- [35] C.Y. Tso, K.C. Chan, C.Y.H. Chao, C.L. Wu, Experimental performance analysis on an adsorption cooling system using zeolite 13X/CaCl₂ adsorbent with various operation sequences, *Int. J. Heat Mass Transf.* 85 (2015) 343–355.
- [36] L.Q. Zhu, C.Y. Tso, W. He, C.L. Wu, C.Y.H. Chao, A field investigation of a solar-powered adsorption cooling system under Guangzhou's climate with various numbers of heat exchangers in the adsorbers, *Sci. Technol. Built Environ.* 23 (8) (2017) 1282–1292.
- [37] K.C. Chan, C.Y. Tso, C.L. Wu, C.Y.H. Chao, Enhancement of the performance of a zeolite 13X/CaCl₂ – water adsorption cooling system by improving adsorber design and operation sequence, *Energy Build.* 2017 (158) (2018) 1368–1378.
- [38] B.B. Saha, I.I. El-Sharkawy, A. Chakraborty, S. Koyama, N.D. Banker, P. Dutta, M. Prasad, K. Srinivasan, Evaluation of minimum desorption temperatures of thermal compressors in adsorption refrigeration cycles, *Int. J. Refrig.* 29 (2006) 1175–1181.
- [39] T.X. Li, R.Z. Wang, J.K. Kiplagat, L.W. Wang, R.G. Oliveira, A conceptual design and performance analysis of a triple-effect solid-gas thermochemical sorption refrigeration system with internal heat recovery, *Chem. Eng. Sci.* 64 (2009) 3376–3384.
- [40] T.F. Qu, R.Z. Wang, W. Wang, Study on heat and mass recovery in adsorption refrigeration cycles, *Appl. Therm. Eng.* 21 (2001) 439–452.
- [41] L.K. Prasad, J.W. McGinity, R.O. Williams III, Electrostatic powder coating: principles and pharmaceutical applications, *Int. J. Pharm.* 505 (2016) 289–302.
- [42] Q.L. Yang, Y.L. Ma, J. Zhu, K. Chow, K.Q. Shi, An update on electrostatic powder coating for pharmaceuticals, *Particuology* 31 (2017) 1–7.
- [43] Y.T. Fang, C. Liu, Z.G. Zhang, X.N. Gao, T. Xu, Y. Yu, J. Gu, A preparation method of an adsorbent coating on a finned tube heat exchanger (Translated from Chinese), China, *Invention Patent*, CN102601024A.
- [44] G. Restuccia, G. Cacciola, Performance of adsorption systems for ambient heating and air conditioning, *Int. J. Refrig.* 22 (1) (1999) 18–26.
- [45] Y.F. Luo, J. Zhu, Y.L. Ma, H. Zhang, Dry coating, a novel coating technology for solid pharmaceutical dosage forms, *Int. J. Pharm.* 358 (2008) 16–22.
- [46] A. Allouhi, T. Kouksou, A. Jamil, Y. Agrouaz, T. Bouhal, R. Saidur, A. Benbassou, Performance evaluation of solar adsorption cooling systems for vaccine preservation in Sub-Saharan Africa, *Appl. Energy* 170 (2016) 232–241.
- [47] E.E. Anyanwu, C.I. Ezekwe, Design, construction and test run of a solid adsorption solar refrigerator using activated carbon/methanol, as adsorbent/adsorbate pair, *Energy Convers. Manag.* 44 (2003) 2879–2892.
- [48] H. Deshmukh, M.P. Maiya, S.S. Murthy, Continuous vapour adsorption cooling system with three adsorber beds, *Appl. Therm. Eng.* 82 (2015) 380–389.
- [49] A. El-Fadar, Novel process for performance enhancement of a solar continuous adsorption cooling system, *Energy* 114 (2016) 10–23.
- [50] N.M. Khattab, A novel solar-powered adsorption refrigeration module, *Appl. Therm. Eng.* 24 (2004) 2747–2760.
- [51] C. Li, R.Z. Wang, L.W. Wang, T.X. Li, Y. Chen, Experimental study on an adsorption icemaker driven by parabolic trough solar collector, *Renew. Energy* 57 (2013) 223–233.
- [52] X.J. Zhang, R.Z. Wang, Design and performance simulation of a new solar continuous solid adsorption refrigeration and heating hybrid system, *Renew. Energy* 27 (3) (2002) 401–415.