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Experimental Investigation of a Zeolite 13X/$CaCl_2$ – Water Adsorption Cooling System

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Abstract

In this study, an adsorption cooling system with a novel composite material (zeolite 13X/$CaCl_2$) as the adsorbent and water as the adsorbate has been built and the system performance is studied experimentally under various working conditions. This particular composite adsorbent was directly coated on the fins of heat exchangers (adsorbent bed), which has never been studied before. The adsorption cooling system consists of two adsorbers, a chilled water tank, a condenser, separate heating and cooling water tanks, and is equipped with measuring instruments and supplementary system components. Under the standard operating condition: adsorber cooling water inlet temperature of 28 °C, desorption temperature of 85 °C, chilled water inlet temperature of 14 °C, adsorption/desorption phase time of 8 minutes and mass recovery time of 22 seconds, the specific cooling power (SCP) recorded is about 376 W/kg, while the coefficient of performance (COP) is calculated at about 0.27.

Keywords – adsorption cooling system, adsorbent, experiment, zeolite

1. Introduction

Climate change and increase in energy costs have motivated industries and research leaders to focus on renewable energy and energy efficiency. Buildings are the major electricity consuming element for urbanized cities. Under a subtropical climate, air-conditioning and especially the cooling system demands the most energy, representing about 30% - 40% of a typical commercial building's electricity consumption [1-2]. Vapor compression chillers (VCC) that operate under a Carnot vapor refrigeration cycle are the major part of the cooling system. Operating VCC is not only carbon unfriendly with high global warming potential, but also uses refrigerants that are ozone depleting. Adsorption cooling systems can become an excellent replacement for the VCC due to their environmental friendliness and energy saving potential, featuring less moving parts and lower noise level and vibration [3-6].

Studies of adsorption cooling systems have been ongoing since the Energy Crisis in the 1970s but have not received enough attention compared to absorption cooling systems. This is because adsorption cooling systems are low in specific cooling power (SCP) as well as coefficient of performance (COP), leading to a bulky system. Making use of a composite adsorbent in the adsorption cooling system is one trend to be developed to enhance the SCP and COP. Therefore, many researchers have devoted their work to develop different types of composite adsorbents for adsorption cooling systems. Saha et al. [7] investigated a two-bed adsorption chiller using a composite adsorbent called SWS-1L ($CaCl_2$ confined in silica gel). SWS-1L has a high water adsorption capacity, which shows a favorable characteristic as an adsorbent for adsorption cooling systems [8]. Recently, Tso et al. [9] built a double-bed adsorption cooling system using the composite adsorbent of zeolite 13X/$CaCl_2$. The results showed that the SCP recorded was about 106 W/kg, while the COP was found to be 0.16 at the most optimized operating condition. However, it should be noted that the thickness of the composite adsorbents packed inside the adsorber is about 6 mm which might be too thick. As a result, the water vapor diffusion in the composite adsorbent is slow, leading to a slow water vapor sorption rate which limits the cooling performance of the adsorption cooling system.

In this study, one of the aims is to build a thermally driven adsorption cooling system using zeolite 13X/$CaCl_2$ – water as the adsorbent-adsorbate working pair. The composite adsorbents were directly coated on the fins of heat exchangers (adsorbent bed) which are different from our previous work [9]. Besides, this paper also aims at investigating the performance of the cooling system under various operating conditions, such as the desorption temperature, phase time, cooling water inlet temperature and evaporating temperature. The SCP is the major figure of merit.

2. Working Princicple of the Adsorption Cooling System

Adsorption cooling systems can be compared to conventional vapor compression cooling systems for air conditioners, chillers or refrigerators in which the electric powered mechanical compressor is replaced by an adsorber. The system can be powered by a rather low driven temperature, e.g. waste heat or solar energy, which makes it attractive for saving electrical energy [10-11]. Besides, the adsorption cooling system can be operated with minimal moving parts; using only valves and water pumps. These result in low vibration, simple mechanics, high reliability and a very long life cycle [12–13].

The adsorption-desorption process is described in an isostere diagram. The ideal cycles consist of four steps as shown in Fig. 1:

1. Isosteric heating: the adsorbent is heated without changing the loading of water vapor.

2. Desorption process: the adsorbent is heated and regenerated at the condenser pressure (P_{cond}). The adsorbent changes its loading from the maximum value X_{max} to the minimum loading X_{min}. In this process, the desorption heat (Q_{des}) is taken up. At the same time, the desorbed refrigerant is condensed in the condenser releasing the heat of condensation at the temperature T_{cond}.

3. Isosteric cooling: the regenerated adsorbent is cooled to reach the conditions for the following adsorption process. The loading stays constant at X_{min}.

4. Isobaric adsorption: the adsorbent adsorbs refrigerant at the pressure P_{eva} of the evaporator. In this process, the loading increases from X_{min} to X_{max} and the heat of adsorption is released. The refrigerant evaporates in the evaporator, producing the cooling effect.

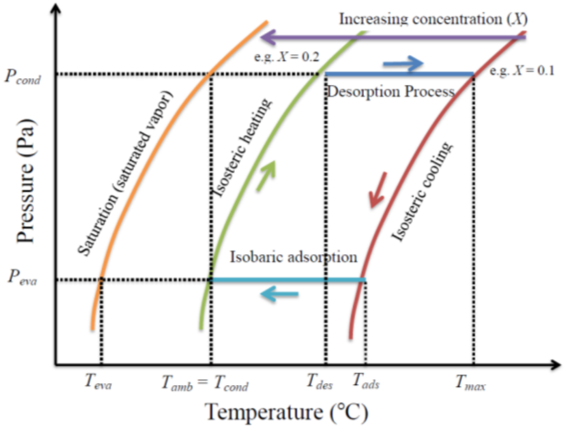

Figure 1 Adsorption cycle in an isostere diagram

As the adsorbent cannot be pumped, these steps have to be carried out consecutively. This implies that the system only produces cooling intermittently during the adsorption step. In order to provide quasi-continuous cooling, a laboratory prototype of a double bed adsorption cooling system was designed and built, and its performance analyzed experimentally under different working conditions. A schematic diagram of the prototype is shown in Fig. 2.

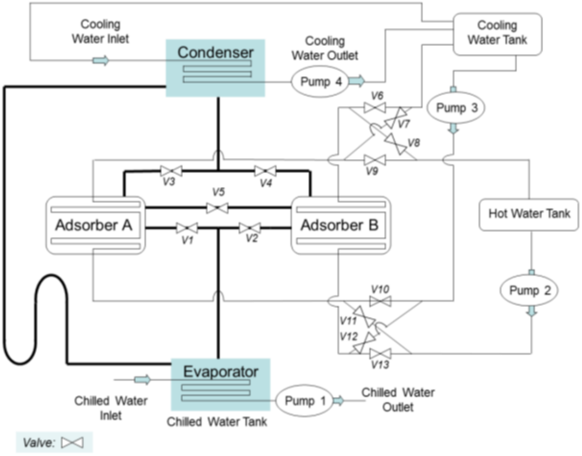

Figure 2 Schematic diagram of the laborabory prototype adsorption cooling system

The cycle has three modes; adsorber A adsorption mode, mass recovery mode and adsorber A desorption mode. The adsorber A adsorption mode and adsorber A desorption mode run alternately while the mass recovery mode runs after the adsorber A adsorption mode or adsorber A desorption mode.

In adsorber A adsorption mode, as shown in Figure 2, valves V1, V4, V7, V8, V10 and V13 are opened, while the other valves remain closed. In the adsorption–evaporation process, water in the chilled water tank evaporates at the evaporation temperature, T_{eva}, and the latent heat, Q_{eva} is removed from the chilled water. The evaporated vapor is adsorbed by the composite adsorbent in adsorber A, where cooling water removes the adsorption heat, Q_{ads}. The desorption–condensation process takes place at pressure P_{cond}. Adsorber B is heated to the temperature, T_{des}, by Q_{des}, provided by the hot water. The desorbed water vapor is cooled to temperature (T_{cond}) in the condenser by cooling water (tap water), which removes the heat, Q_{cond}. The condensed water returns to the evaporator via the U-tube connecting the condenser and chilled water tank to complete the cycle.

In the mass recovery mode, as shown in Fig. 2, only valve V5 is opened while the other valves remain closed. The mass recovery is beneficial to improve the adsorption cycled refrigerant (water vapor) of an adsorption cooling system. In a typical mass recovery process, the pressure of adsorber B at the end of the desorption process is higher than at the end of the adsorption process. Next, the high pressure adsorber needs to be cooled and depressurized while the low pressure adsorber needs to be heated and pressurized. Then the two adsorbers may be directly interconnected with a simple device and the refrigerant vapor will flow from the high-pressure bed to the low pressure bed. The pressure of adsorber B decreases due to mass outflow and this will again cause desorption of adsorber B. Meanwhile, the pressure of adsorber A increases due to mass inflow and will cause further adsorption. The process continues until the two adsorbers reach the same pressure. Then the connection is broken and each adsorber goes on with the heating and cooling process just as in the adsorption mode and desorption mode. This mass recovery process is expected to accelerate the circulation and enhance the cycle cooling power [14-16].

Lastly, in the adsorber A desorption mode; valves V2, V3, V6, V9, V11 and V12 are opened while the other valves remain closed. In this mode, adsorber B adsorbs while adsorber A desorbs.

3. Description of the Adsorption Cooling System Prototype

The adsorber is the most important element of an adsorption cooling system. Because of the poor thermal conductivity of the adsorbent materials commonly used in adsorption cooling systems, the heat and mass transfer abilities of the adsorbers that affect the performance of the system should be considered carefully during the design of the adsorbers. In this study, the composite adsorbents were directly coated on the fins of heat exchangers (adsorbent beds). Fig. 3 shows a photograph of a heat exchanger with and without coating of the composite adsorbent. One heat exchanger can carry about 2 kg of composite adsorbent (zeolite 13X/$CaCl_2$). The thickness of the composite adsorbent coated on the fin surfaces is less than 1 mm. As the adsorption cooling system does not consist of any strong vibrating components, it operates stably. This implies that the composite adsorbents did not fall down from the adsorbent bed. Finally, the heat exchanger (adsorbent bed) coated with the composite adsorbents was put inside a large vacuum chamber, forming an adsorber. Three photographs of the adsorption cooling system prototype with three different views are shown in Fig. 4.

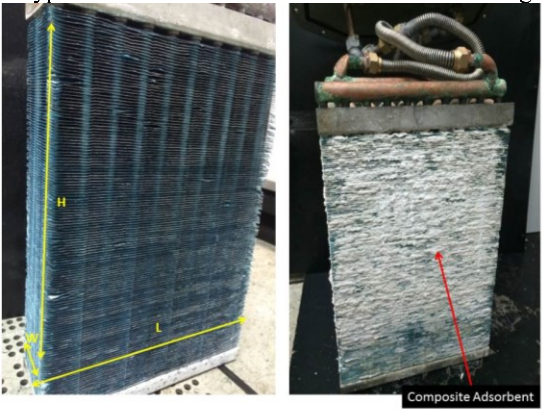

Figure 3 Photographs of the heat exchanger (adsorbent bed) with and without coating of the composite adsorbent

[Remark: Dimensions of heat exchanger: 264 mm (L) X 100 mm (W) X 420 mm (H);

Aluminum fins pitch: 1.8 mm; thickness of the fins: 0.115 mm]

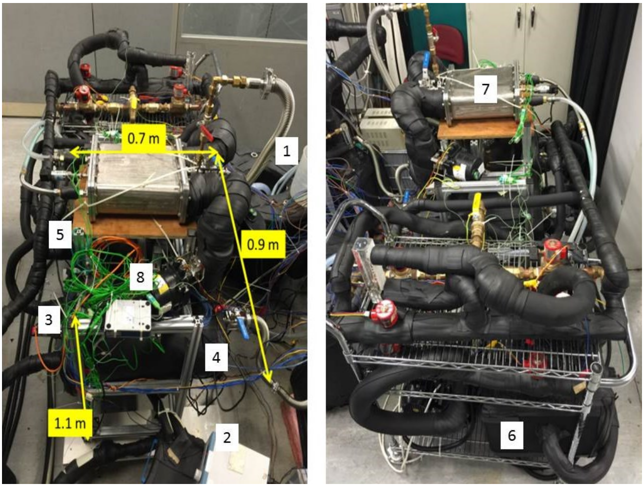

Figure 4 A prototype of the adsorption cooling system (three different views)

[Remarks: 1: cooling water tank; 2: isothermal water circulator; 3: chilled water tank (evaporator); 4: Adsorber A; 5: Adsorber B; 6: hot water tank; 7: condenser; 8: control system]

Regarding the other devices, such as chilled water tank, conderser, cooling water tank, and hot water tank, those are all similar to our previous work [9]. The standard operating conditions for the adsorption cooling system are shown in Table 1, and also for various conditions as listed in Table 2. Equation (1) is used to calculate the COP of the experimental prototype for different operating conditions. Specifically, this is referred to as the time-average COP:

$$COP = \int_0^{t_{cycle}} \frac{Q_{chill}}{Q_{des}} dt \bigg/ \int_0^{t_{cycle}} dt \tag{1}$$

where Q_{chill} and Q_{des} represent the cooling output power and thermal input power, respectively, t_{cycle} is the cycle time, including two adsorption/desorption phase times as well as the mass recovery cycle time. They are calculated from the measured water flow rates, the isobaric specific heat capacities, and inlet and outlet temperatures of the chilled water tank (evaporator) and hot water tank as shown in equation (2) and equation (3) below, respectively:

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

$$Q_{des} = \dot{m}_{hot} c_{p,water} (T_{hot,in} - T_{hot,out}) \tag{3}$$

where $\dot{m}_{chill}$ and $\dot{m}_{hot}$ represent the mass flow rates of chilled water and hot water, respectively, and $c_{p,water}$ represents the specific heat capacity of water. Equation (4) is used to calculate the SCP of the adsorption cooling systems:

$$SCP = \dot{m}_{chill} c_{p,water} \int_0^{t_{cycle}} (T_{chill,in} - T_{chill,out}) dt \bigg/ W t_{cycle} \tag{4}$$

where W represents the weight of the composite adsorbent (2 kg zeolite 13X/$CaCl_2$).

Table 1. Standard operating conditions for the adsorption cooling system

Parameters	**Symbol**	**Value**	**Unit**
Hot water inlet (desorption) temperature	$T_{hot,in}$	85	°C
Adsorber cooling water inlet temperature	$T_{cool,in}$	28	°C
Chilled water inlet temperature	$T_{chill,in}$	14	°C
Chilled water mass flow rate	$\dot{m}_{chill}$	5	kg/min
Hot water mass flow rate	$\dot{m}_{hot}$	14	kg/min
Cooling water mass flow rate	$\dot{m}_{cool}$	16	kg/min
Adsorption/desorption phase time	t_{phase}	8	mins
Mass recovery time	t_{mr}	22	seconds

Table 2. Varied operating conditions for the adsorption cooling system

Parameters	Symbol	Value	Unit
Hot water inlet (desorption) temperature	$T_{hot,in}$	55, 65, 75, 95	°C
Adsorber cooling water inlet temperature	$T_{cool,in}$	19, 32, 43	°C
Chilled water inlet temperature	$T_{chill,in}$	8, 11, 17, 20	°C
Adsorption/desorption phase time	t_{phase}	2, 4, 12, 16, 20	mins

4. System Optimization

The performance of the prototype was investigated experimentally under various conditions. Since the thermal input power is obtained by the temperature difference between the inlet and outlet of the hot water tank, heat loss to the ambient environment is included in the calculation. The energy loss is mainly from the adsorbers, hot and cooling water tanks and piping system through which the heat transfer fluid (water) circulates. Fig. 5 shows experimental temperature profiles of the heat transfer fluid at a typical operating condition. The delivered chilled water outlet temperature is always below the inlet temperature throughout the whole cycle, showing that the cooling process is steady and successfully produces the cooling effect.

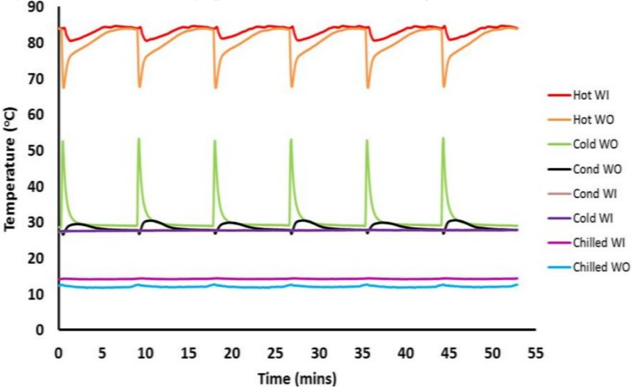

Figure 5. Experimental heat transfer fluid temperature profiles

4.1 *Effect of desorption temperature and adsorption/desorption phase time on the SCP and COP*

The desorption temperature is one of the major factors affecting the performance of adsorption cooling systems. Fig. 6 shows the effect of the desorption temperatures on the SCP and COP. It is found that the SCP increases almost monotonically with the desorption temperature from 55 °C to 95 °C. Since water vapor is desorbed faster at the higher desorption temperature, the adsorbent is drier so the driving force for adsorption is higher, allowing more water vapor to be adsorbed during the next adsorption process. In other words, the higher the desorption temperature, the better the SCP of the adsorption cooling system. However, it should be emphasized that the desorption temperature depends on the real situation. Since the intensity of sunlight is not steady, the achievable hot water temperature may not be high. Therefore, standard hot water inlet temperature was selected to be 85 °C. On the other hand, it is interesting to note that the thermal energy input should actually come from renewable energy (e.g. solar energy or waste heat) which is free of charge or from natural resources. Therefore, the thermal COP values shown in this study are just for reference and comparison with other studies. SCP is indeed a very important parameter which indicates how large the adsorption cooling system is and the cooling power of the adsorption cooling system.

Fig. 7 shows the effect of adsorption/desorption phase time on the SCP and COP. All system parameters remained the same as shown in Table 1, except for the adsorption/desorption phase time which was considered as the varied operating parameter. Besides, it should be pointed out that the adsorption/desorption phase time was controlled by an automatic control system operating all valves and pumps, instead of by changing the hot water mass flow rate, etc. From Fig. 7, it is shown that 8 minutes is the best adsorption/desorption phase time for this adsorption cooling system. This is because for shorter adsorption/desorption phase times, the desorption process is incomplete, leading to diminish the adsorption capacity of adsorbents. As a result, the SCP is low at a shorter phase time. For longer phase times, the SCP decreases due to the rapid diminution of adsorption capacity of the adsorbents during the last few minutes. As a very thin layer of the composite adsorbent is formed on the fins of the heat exchanger compared to our previous study where the composite adsorbents were packed in between the copper circular fins (i.e. the thickness is about 6 mm), the diffusion process between the water vapor and the composite adsorbents is much faster using the coating strategy, leading to a significantly shorter adsorption/desorption phase time (i.e. the optimized adsorption/desorption phase time is about 8 minutes in this system, while it was 25 minutes in our previous study [9]).

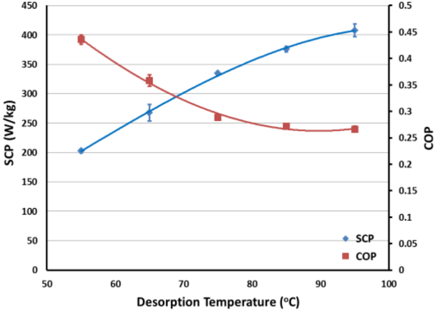

Figure 6. Effect of desorption temperature on the SCP and COP

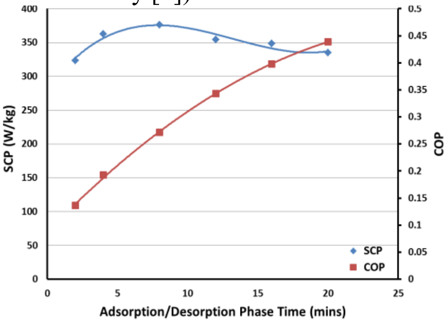

Figure 7. Effect of adsorption/desorption phase time on the SCP and COP

4.2 Effect of cooling water inlet temperature and chilled water inlet temperature on the SCP and COP

The cooling water inlet temperature is one decisive factor on the performance of adsorption cooling systems because it influences not only the condensation process but also the adsorption process. A high cooling water inlet temperature results in a high inlet temperature supply to the condenser and adsorption chamber. Consequently, both the desorption and adsorption process performance deteriorates, losing more refrigerating power. Fig. 8 shows the effect of cooling water inlet temperature on the SCP and COP. The lower the cooling water inlet temperature, the higher the SCP and COP since more water vapour is adsorbed by the composite adsorbent at a lower temperature for a given cycle time. To save energy when removing the adsorption heat, it is desirable to use cooling water at room temperature. However, due to the operation of a water pump, the cooling water inlet temperature averages 28 ^{o}C. Under this condition, the SCP value can be achieved at about 376 W/kg with the COP about 0.27.

Fig. 9 shows the effect of chilled water inlet temperature (evaporating temperature) on the SCP and COP. Both SCP and COP rise with an increase in chilled water inlet (evaporating) temperatures. This is because the higher the chilled water inlet (evaporating) temperature, the higher the evaporating pressure is, leading to a larger amount of water vapour to be adsorbed by the composite adsorbent. As a result, the SCP and COP increase with the chilled water inlet (evaporating) temperature.

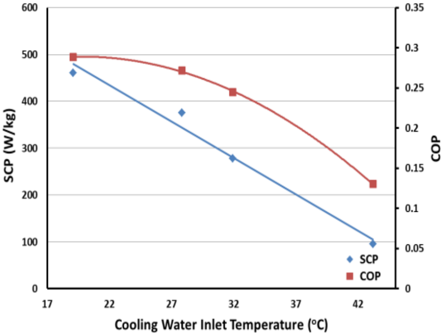

Figure 8. Effect of cooling water inlet temperature on the SCP and COP

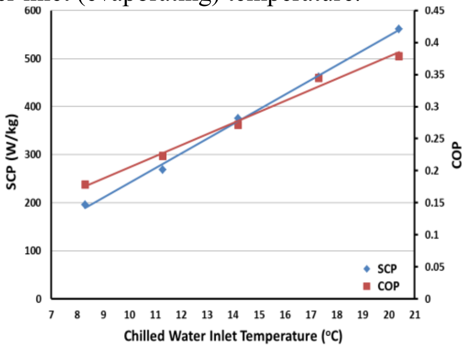

Figure 9. Effect of chilled water inlet (evaporating) temperature on the SCP and COP

5. Conclusions

In this study, a double-bed composite adsorbent (zeolite 13X/$CaCl_2$)–water adsorption cooling system has been developed. The composite adsorbents were coated directly on the fins of heat exchangers, leading to enhance the diffusion rate between the water vapor and composite adsorbents. Under the most optimized operating condition, a SCP of 376W/kg is achieved, while the COP is calculated at about 0.27. In addition, a comparison is made between the present work and our previous study [9]. It should be noted that the major difference between these two works is the design of the adsorber (i.e. coating of the composite adsorbents on the fins of heat exchangers or packing the composite adsorbents between the copper circular fins). Approximately, a

250% improvement in SCP was obtained, proving that coating the adsorbents on the fins of the heat exchanger substantially improved the cooling performance of the adsorption cooling systems. To conclude, by using a proper design of the adsorber (i.e. coating strategy), together with a novel composite adsorbent material, the SCP and COP of the adsorption cooling systems can be substantially enhanced. In other words, this novel composite material has potential for use in adsorption cooling systems.

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