EXPERIMENTAL INVESTIGATION OF A DOUBLE-BED ADSORPTION COOLING SYSTEM FOR APPLICATION IN GREEN BUILDINGS

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ABSTRACT

In this study, an adsorption cooling system with silica gel as the adsorbent and water as the adsorbate was built and the system performance was studied experimentally under various working conditions. The adsorption cooling system contains two adsorbers in a u-tube and circular plate fin structure, an evaporator (chilled water tank), two condensers, one heating and one cooling water tank, and is equipped with measuring instruments and supplementary system components. Under the standard operation condition: adsorber cooling water inlet temperature about 34 ℃, desorption temperature of 80 ℃, evaporating temperature of 14 ℃ and adsorption/desorption phase time of 15 minutes, the coefficient of performance (COP) of the adsorption cooling system was recorded at about 0.3 while the specific cooling power (SCP) was about 39.1 W/kg.

INTRODUCTION

Global warming and energy shortage issues have been receiving great attention in recent years all over the world. Among various technologies being developed to alleviate these problems, adsorption cooling systems powered by solar energy or waste heat have good potential in terms of saving energy. These systems need neither CFCs nor HCFCs as the working fluid and limited electricity is needed to drive them [1-4]. Silica gel - water as an adsorbent - adsorbate pair is widely used in adsorption cooling systems since silica gel requires a low regeneration temperature while water has a relatively high latent heat of vaporization. Additionally, this working pair is non-toxic and stable. Although adsorption cooling systems are thought to be very promising for the future application of solar cooling and waste heat recovery, the wide use of this technology is not yet possible due to poor COP values and the high product cost of the systems [5-7].

Many researchers have devoted their work to adsorption refrigeration technology and many studies have been conducted. As part of that research, silica gel – water adsorption cooling systems have been analytically and experimentally investigated [8-10]. Saha et al. [10] experimentally investigated a double-stage, four bed, non-regenerative adsorption chiller powered by solar/waste heat sources between 50 and 70 ℃. The prototype studied produces chilled water at 10 ℃ and has a cooling power of 3.2 kW with a COP of 0.36, when the heat source and heat sink temperatures are 55 and 30 ℃, respectively. Boelman et al. [11] experimentally and numerically studied a commercially available silica gel – water adsorption chiller. The highest experimental COP values above 0.4 were obtained with a hot water inlet temperature of 50 ℃ and cooling water inlet temperature of 20 ℃. This study aims at building a thermally driven adsorption cooling system using silica gel – water as the adsorbent – adsorbate pair, using a novel design consisting of a u-tube and circular plate fin structure as the adsorber. Most importantly, the performance of the cooling system in various operating conditions, such as desorption temperature, adsorber cooling water temperature, evaporating temperature, cycle time and heat transfer fluid (water) mass flow rate are investigated.

NOMENCLATURE

$C_{p,water}$	[J/kgK]	Specific heat capacity of water
COP	[-]	Coefficient of performance
$\dot{m}$	[kg/min]	Heat transfer fluid mass flow rate
P	[Pa]	Pressure
Q	[W]	Cooling capacity
SCP	[W/kg]	Specific cooling power
T	[K]	Temperature
t	[second]	Time
V	[-]	Valve
W	[kg]	Mass
X	[kg/kg]	Amount adsorbed (mass of water vapour per mass of dry adsorbent)

Subscripts
ads	adsorption
amb	ambient

chill	chilled water
cond	condenser/condensation
cool	cooling water in adsorber/desorber
cycle	cycle
des	desorption
eva	evaporator/evaporation
hmr	heat and mass recovery
hot	hot water
max	maximum
in	inlet
out	outlet

WORKING PRINCIPLE OF THE ADSORPTION COOLING SYSTEM

The adsorption cooling system can be compared to conventional cooling systems for air conditioners, chillers or refrigerators but with the electrically powered mechanical compressor being 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 in terms of saving electrical energy. In addition, the adsorption cooling system can be operated without moving parts; only solenoid vacuum valves are used. This results in low vibration, mechanical simplicity, high reliability and a very long life span [12-14].

The adsorption-desorption process is described in an isostere diagram. The ideal cycles consist of four steps as shown in Figure 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} (taking $X = 0.2$ as an example) to the minimum loading X_{min} (taking $X = 0.1$ as an example). 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.

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 Figure 2.
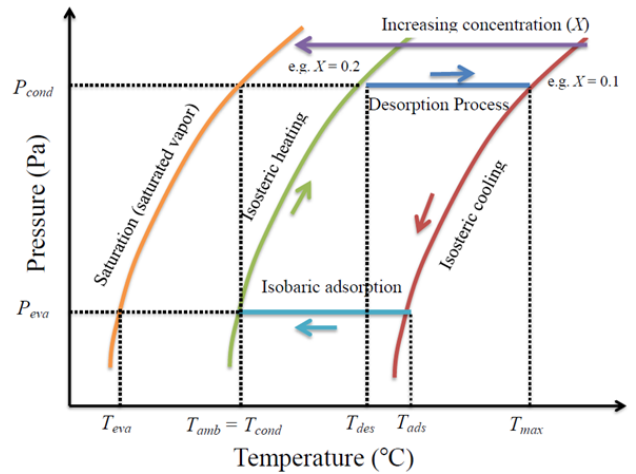

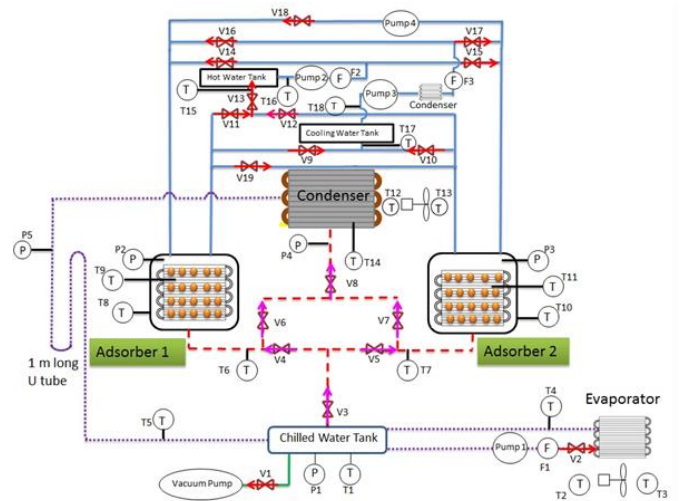**Figure 1** Adsorption cycle in an isostere diagram

Figure 2 Schematic diagram of the laboratory prototype adsorption cooling system

[P: pressure transducers; T: K-type thermocouples; F: flow meters; V1: manual vacuum ball valve; V2: manual ball valve; V3-V8: solenoid vacuum valves; V9-V19: solenoid valves with non-return values connected in series; pump 1 - pump 4: circulation water pumps].

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

In adsorption mode (adsorber 1 as a target), as shown in Figure 2, valves V2, V3, V4, V7, V8, V9, V12, V13, V15 and V16 are opened, while valves V5, V6, V10, V11, V14, V17, V18 and V19 are closed. Valve 1 is opened only before running the system in order to lower the pressure inside the adsorbers and chilled water tank. After the system starts to run normally, the vacuum pump is removed. In this mode, adsorber 1 adsorbs while adsorber 2 desorbs. In the adsorption-evaporation process, refrigerant (water) in the chilled water tank evaporates at the evaporation temperature, T_{eva}, and the seized heat, Q_{eva} is removed from the chilled water tank. The evaporated vapor is adsorbed by the silica gel adsorbent in

adsorber 1, where cooling water removes the adsorption heat, Q_{ads}. The desorption-condensation process takes place at pressure P_{cond}. The desorber (adsorber 2) is heated to the temperature (T_{des}) by Q_{des}, provided by the heat (e.g. waste heat) in the hot water tank. The resulting refrigerant vapor is cooled to temperature (T_{cond}) in the condenser, which removes the heat, Q_{cond}. The condensed refrigerant returns to the evaporator via the U-tube connecting the condenser and evaporator to complete the cycle. After running in adsorption mode for a period of time, the cycle is continued by changing into heat and mass recovery mode.

In the heat and mass recovery mode, as shown in Figure 2, valves V2, V4, V5, V6, V7, V18 and V19 are opened while V3, V8, V9, V10, V11, V12, V13, V14, V15, V16 and V17 are closed. The heat recovery process can recover some heat during mode switching between the adsorber and the desorber. In this process, the heat transfer fluid flows through two adsorbers to recover heat via their temperature difference. By circulating the thermal fluid between the two adsorbers adiabatically, the energy efficiency can be increased significantly [15]. Mass recovery is also beneficial to improve the adsorption cycled refrigerant (water vapor) of an adsorption cooling system. In a typical mass recovery process, the pressure of adsorber 2 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 2 decreases due to mass outflow and this will again cause desorption of adsorber 2. Meanwhile, the pressure of adsorber 1 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, as it only involves direct mass flow while the pressure balance is much faster than the temperature balance via the heat-transfer medium.

Lastly, in the desorption mode (adsorber 1 as a target); valves V2, V3, V5, V6, V8, V10, V11, V13, V14 and V17 are opened while V4, V7, V9, V12, V15, V16, V18 and V19 are closed. In this mode, adsorber 2 adsorbs while adsorber 1 desorbs. Again, after running in desorption mode for a period of time, the cycle returns to the heat and mass recovery mode. After that, the cycle goes to adsorber 1 adsorbs mode while adsorber 2 desorbs.

DESCRIPTION OF THE ADSORPTION COOLING SYSTEM

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 should be considered carefully during the design process. In this study, an adsorber was designed and built based on this

consideration. Each adsorber consists of 14 cylindrical shell units, covered with a stainless steel metal screen mesh with a nominal pore size of 74 microns. Figure 3 shows a photograph of a cylindrical shell unit (u-tube structure). The adsorbents are inserted between the circular fins. Each adsorber can be filled with 9 kg of silica gel adsorbent material. The silica gel adsorbent having an average particle size 0.42 – 2 mm was bought from NACALAI TESQUE, INC, Kyoto, Japan. The isotherm of this silica gel is well-known, of which the adsorption capacity is directly proportional to the vapour pressure within the operation range of adsorption cooling systems. Two thermocouples are located in the adsorber to record the temperature of the adsorbents. 14 cylindrical shells are put together into a large cylindrical vacuum chamber (adsorber) and are connected in series by copper piping as shown in Figure 4.
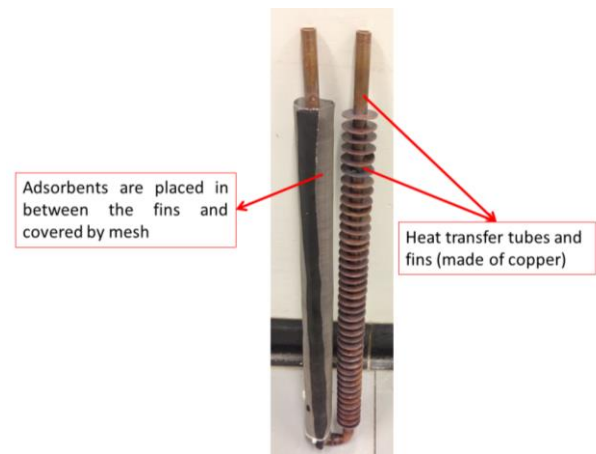
Figure 3 One cylindrical shell unit (u-tube structure) used in the adsorber
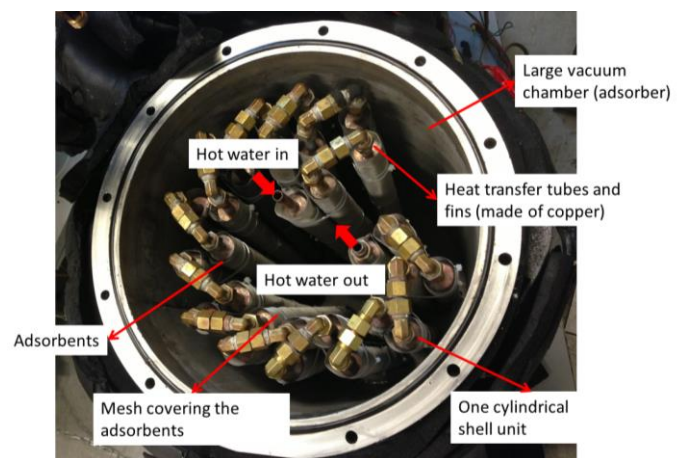
Figure 4 14 cylindrical shells in a large vacuum chamber (adsorber)

Control system and calculations

A 2.2 kW electrical immersion heater is inserted into the hot water tank in order to generate the heat for the desorption process of the adsorption cooling system. An electrical heater is used instead of solar thermal or a waste heat capturing

system because the main interest of this study is the performance of the silica gel adsorbents under various well-controlled operating conditions. A PID temperature controller was used to control the temperature inside the hot water tank to prevent overheating and to control the desorption temperature (hot water inlet temperature) for different operating conditions.

All the thermocouple and pressure transducer measurements were recorded by data acquisition (DAQ) devices from National Instrument. The thermocouple signals were recorded by SCXI-1102 32-Channel Thermocouple/Voltage Input Module with SCXI-1324 terminal block equipped in the SCXI-1001 chassis, while the pressure transducer signals were recorded by USB-6229 USB DAQ device connected to a computer. NI LabVIEW (version 8.6) software was used to build a virtual DAQ program. Data was recorded every 5 seconds and stored in the computer's hard disk. Another LabVIEW program was built to control the solenoid vacuum valves through a SCXI-1160 16-Channel General-Purpose Relay Module on SCXI-1001. The program can control the valves individually or in a group, allowing phase changes to be completed in one click.

The standard operating conditions for the adsorption cooling system are shown in Table 1 while varied operating conditions are listed in Table 2.

Table 1 Standard operating condition for the adsorption cooling system

Parameters	Symbol	Value	unit
Hot water inlet temperature	$T_{hot,in}$	80	^{o}C
Hot water mass flow rate	$\dot{m}_{hot}$	8	kg/min
Adsorber cooling water inlet temperature	$T_{cool,in}$	34	^{o}C
Adsorber cooling water mass flow rate	$\dot{m}_{cool}$	8	kg/min
Chilled water inlet temperature	$T_{chill,in}$	14	^{o}C
Chilled water mass flow rate	$\dot{m}_{chill}$	3.6	kg/min
Adsorption/desorption phase time	t_{cycle}	15	mins
Heat and mass recovery time	t_{hmr}	50	seconds

Table 2 Varied operating conditions for the adsorption cooling system

Parameters	Symbol	Value	unit
Hot water inlet (desorption) temperature	$T_{hot,in}$	55, 60, 65, 70, 75, 80, 85, 90, 95	^{o}C
Hot water mass flow rate	$\dot{m}_{hot}$	4, 6, 8, 10	kg/min
Adsorber cooling water inlet temperature	$T_{cool,in}$	20.5, 27, 32.5, 34	^{o}C
Adsorber cooling water mass flow rate	$\dot{m}_{cool}$	4, 6, 8, 10	kg/min
Chilled water inlet temperature	$T_{chill,in}$	8, 10, 12, 14, 16, 18, 20	^{o}C
Chilled water mass flow rate	$\dot{m}_{chill}$	1.6, 3.6, 5.6, 7.6	kg/min
Adsorption/desorption phase time	t_{cycle}	5, 7.5, 10,15, 20, 25, 30	mins

Equation (1) is used to calculate the coefficient of performance (COP) of the experimental prototype for different operating conditions. Specifically, this refers to the time-average COP:

$$COP = \frac{\int_0^{t_{cycle}} \left(\frac{Q_{chill}}{Q_{des}} \right) dt}{\int_0^{t_{cycle}} dt} \tag{1}$$

where Q_{chill} and Q_{des} represent the cooling output power and thermal input power, respectively. They are calculated from the measured 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. Equation (4) is used to calculate the specific cooling power (SCP) of the adsorption cooling systems:

$$SCP = \frac{Q_{chill}}{W} \tag{4}$$

where W represents the weight of the silica gel adsorbent.

RESULTS AND DISCUSSIONS

The performance of the prototype was investigated experimentally under various conditions. A photograph of the whole adsorption cooling system prototype is shown in Figure 5. An isothermal water circulator was used to provide a steady chilled water inlet temperature to the adsorption cooling system enabling an accurate evaporating temperature to be obtained during the measurement. Since the thermal input power was 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 was mainly from the adsorbers, hot and cooling water tanks, piping system through which heat transfer fluid (water) circulates, and heat capacities of the metal and heat transfer fluid (water).
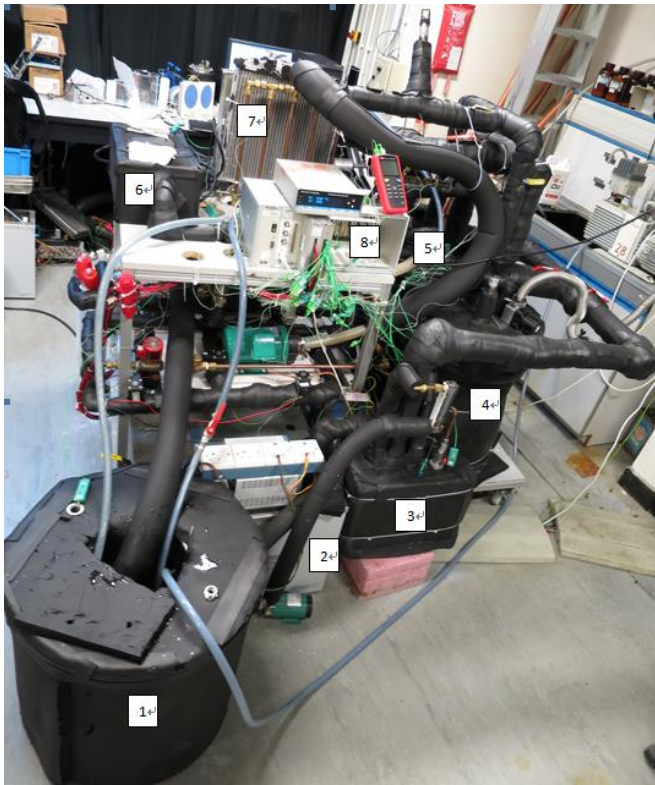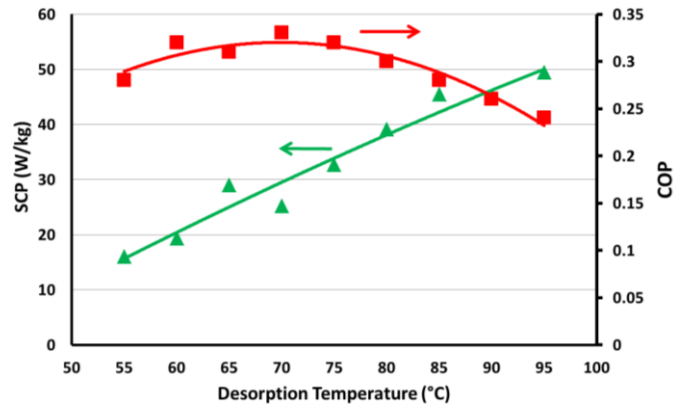
Figure 5 A prototype of the adsorption cooling system
[Remarks: 1: cooling water tank; 2: isothermal water circulator; 3: chilled water tank (evaporator); 4: Adsorber 1; 5: Adsorber 2; 6: hot water tank; 7: condenser; 8: control system.]

Effect of desorption temperature on the SCP and COP

The desorption temperature is one major factor affecting the performance of adsorption cooling systems. Figure 6 shows the effect of the desorption temperature on the SCP and COP. Theoretically, the COP should increase, along with the desorption temperature, to a specific temperature and thereafter remain unchanged as the temperature continues to rise. As shown in Figure 6, the COP increases when the desorption temperature is lower than 70 °C, but it decreases significantly for desorption temperatures higher than 70 °C. This can be attributed to an increase in heat loss at higher desorption temperatures. For the lower desorption temperatures, the heat loss is smaller compared with the higher desorption temperatures. The results of the SCP are in good agreement with the prediction, increasing 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.

However, it should be remembered that the thermal energy input should actually come from renewable energy (e.g. solar energy or waste heat) which are 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. In reality, the COP value is meaningless for adsorption cooling systems. However, SCP is a very important parameter, indicating how large the adsorption cooling systems are and the

amount of cooling power of the adsorption cooling systems. Hence, the larger the SCP, the smaller the size of the adsorption cooling system for the same cooling output. Considering this, a higher desorption temperature should be selected based on the results shown in Figure 6. However, a higher desorption temperature will limit the application value. After considering the range of low grade waste heat and solar energy, 85 °C is a suitable desorption temperature for adsorption cooling systems. Therefore, 85 °C is utilized in the following study as the desorption temperature for this adsorption cooling system prototype.

Figure 6 Effect of desorption temperature on the SCP and COP

## Effect of adsorption/desorption phase time on the SCP and COP

Figure 7 shows the effect of adsorption/desorption phase time on the SCP and COP performance of the adsorption cooling system. The desorption temperature is set at 85 °C as suggested previously, while the other conditions are as shown in Table 1 (except for the adsorption/desorption phase time since it is the parameter being studied in this section). There exists a peak between 10 and 15 minutes for the SCP and at about 15 minutes for the COP. For shorter adsorption/desorption phase times, the desorption process is incomplete, leading to diminish the adsorption capacity of silica gel adsorbent. As a result, the SCP and COP are low at a shorter phase time. For longer adsorption/desorption phase times, the SCP decreases due to the rapid diminution of adsorption capacity of the silica gel adsorbent during the last few minutes. In short, the adsorption/desorption phase time for this adsorption cooling system prototype using silica gel as the adsorbent is about 15 minutes since it not only shows a higher SCP, but also the COP is maximized.
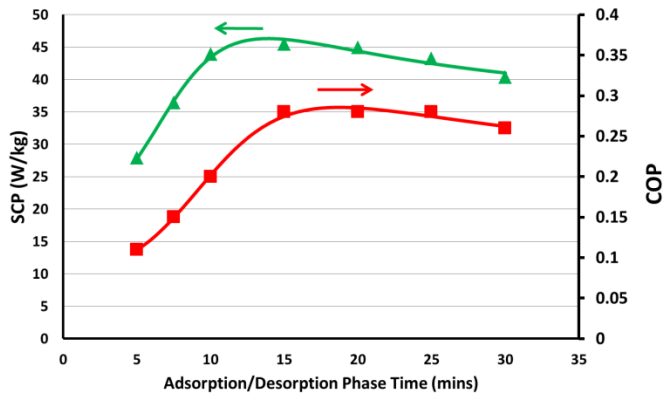
Figure 7 Effect of adsorption/desorption phase time on the SCP and COP

Effect of the hot water mass flow rate on the SCP and COP

Hot water is used to heat the adsorbent during the desorption process. More heat can be transferred to the adsorbers over the same duration with a higher hot water mass flow rate, allowing more water vapor to be desorbed out. Hence, a higher hot water mass flow rate should result in higher COP and SCP. In the experimental results, the COP, however, decreased after 8 kg/min in terms of the hot water mass flow rate as shown in Figure 8. This is simply because more heat is lost to the surroundings under higher hot water mass flow rate. The effect is similar to that caused by changing the desorption temperature as previously discussed. For the lowest hot water flow rate, 4 kg/min, the COP also decreases, possibly because the adsorber cannot be desorbed effectively under this slow flow rate. The effect on SCP is also shown in Figure 8. There is almost no change in SCP and it can be concluded that the hot water mass flow rate does not have an apparent effect on SCP. Therefore, in order to optimize the COP value, 8 kg/min is chosen as the hot water mass flow rate for this adsorption cooling system prototype.
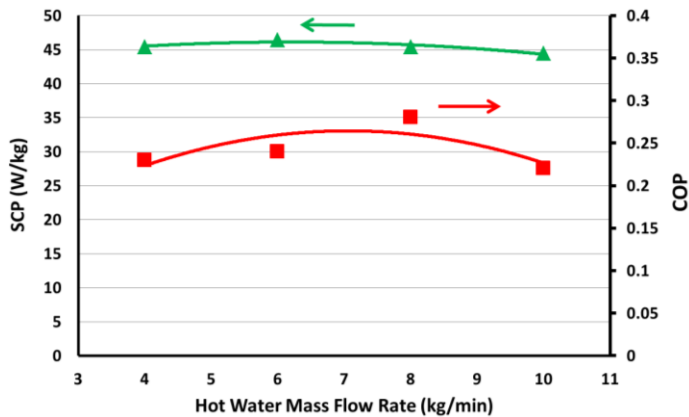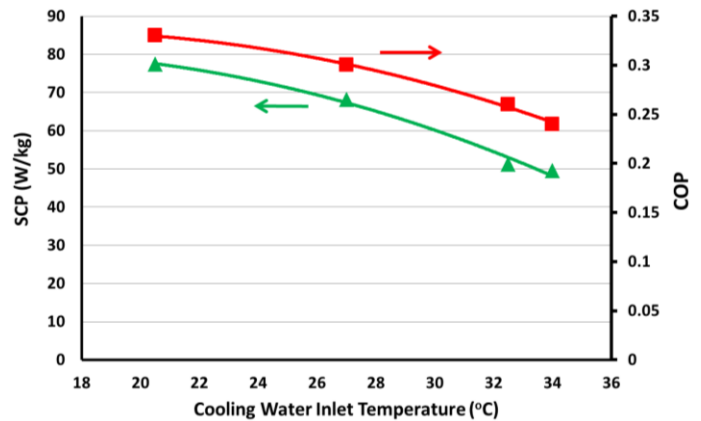

Figure 8 Effect of hot water mass flow rate on the SCP and COP

Effect of cooling 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. Figure 9 shows the effect of cooling water inlet temperature on the SCP and COP. The lower cooling water inlet temperature, the higher SCP and COP since more water vapour is adsorbed by the silica gel 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 27 °C. Under this condition, the SCP value can still be achieved at about 68 W/kg with the COP about 0.3.

Figure 9 Effect of cooling water inlet temperature on the SCP and COP

Effect of the cooling water mass flow rate on the SCP and COP

As previously discussed, cooling water is used to cool the adsorber during the adsorption process because adsorption of adsorbate (water vapor) generates heat. The adsorber also has to be cooled after the high temperature desorption process. If the temperature of the adsorber can be decreased faster and maintained at a low level, a higher SCP and COP will be obtained. Figure 10 shows the influence of cooling water mass flow rate on the performance of SCP and COP. It was found that the COP increases slightly from 4 kg/min to 10 kg/min. This increase, however, is relatively small. Regarding the SCP, it seems to be steady after the cooling water mass flow rate of 7 kg/min. Considering this, 7 kg/min was chosen as the cooling water mass flow rate for this adsorption cooling system.
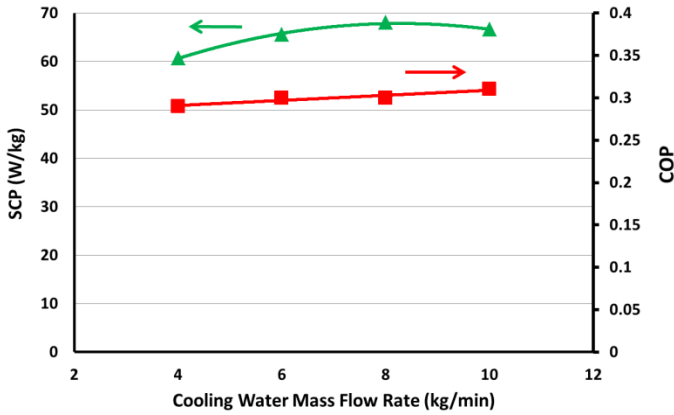
Figure 10 Effect of cooling water mass flow rate on the SCP and COP

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

Figure 11 shows the SCP and COP variations with different chilled water inlet temperatures. 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 silica gel adsorbent. As a result, the SCP and COP increase with the chilled water inlet (evaporating) temperature. For a vapor compression cooling system, the chilled water inlet temperature is about 14 ^{o}C. Therefore, 14 ^{o}C was selected as the chilled water inlet (evaporating) temperature for this adsorption cooling system in order to simulate a real situation and to allow a fair comparison with vapor compression systems.
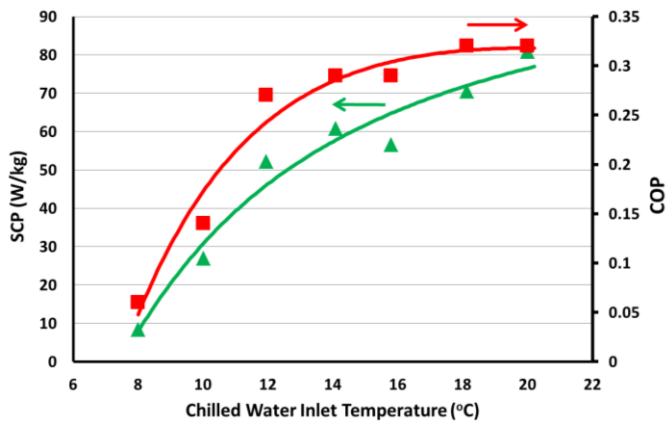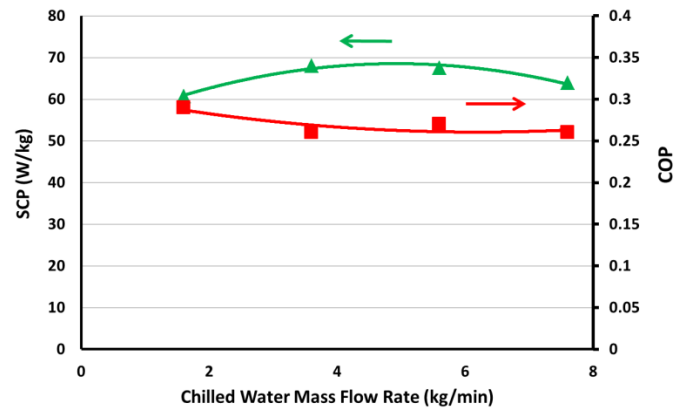

Figure 11 Effect of chilled water inlet (evaporating) temperature on the SCP and COP

Effect of the chilled water mass flow rate on the SCP and COP

Figure 12 shows the influence of chilled water mass flow rates. As the flow rate is increased, the SCP first increases and then slightly decreases. This decrease may be due to some heat gain at a higher flow rate from the surroundings. Regarding the COP, there is almost no change. In detail, it varies between 0.29 and 0.32 and it can therefore be concluded that the chilled water mass flow rate does not hugely affect the COP, but there exists a peak value of the SCP. To conclude, 5 kg/min could be

selected as the chilled water mass flow rate for this particular adsorption cooling system prototype since it gives the highest value of SCP.

Figure 12 Effect of chilled water mass flow rate on the SCP and COP

Temperature profile of the heat transfer fluid (water)

Figure 13 shows experimental temperature profiles of the heat transfer fluid inlets and outlets in different locations obtained under typical working conditions. The delivered chilled water outlet temperature is always below the inlet temperature throughout the whole cycle, showing that the cooling process is steady and successful in producing the cooling effect. The difference in chilled water temperature is about 6 ^{o}C. For this typical working condition (85 ^{o}C desorption temperature, 7 kg/min hot water mass flow rate, 27 ^{o}C cooling water inlet temperature, 8 kg/min cooling water mass flow rate, 1.6 kg/min chilled water inlet temperature, 15 mins adsorption/desorption phase time, 50 s heat and mass recovery time), the experimental cooling capacity value is about 560 W, the SCP is about 62.2 W/kg and the COP is about 0.29.
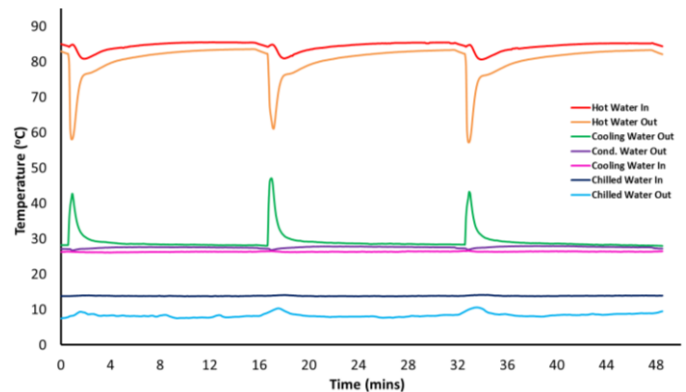
Figure 13 Experimental heat transfer fluid temperature profiles

CONCLUSION

The effects of operating conditions on the SCP and COP of a double-bed silica gel adsorbent – water adsorption cooling system with copper u-tubes and circular plate fin structure

adsorbers has been experimentally investigated. The following conclusions are drawn from the foregoing discussion:

1. The system performance is strongly dependent on the operating conditions such as desorption temperature, cooling water inlet temperature, chilled water inlet (evaporating) temperature and adsorption/desorption phase times. However, the system performance does not hugely depend on the flow rate of the heat transfer fluid (water).

2. In order to obtain optimal performance, an appropriate adsorption/desorption phase time should be selected. There exists a maxima SCP value with the adsorption/desorption phase time of about 15 minutes under the operating conditions in this study.

3. Under the standard operating condition, a cooling power of 352 W and a COP of 0.3 can be obtained. The corresponding SCP is about 39.1 W/(kg silica gel). With slightly higher desorption temperature (85 ^{o}C) along with a lower cooling water inlet temperature (27 ^{o}C), a SCP of 68 W/kg can be achieved, making about 74% improvement compared with the standard operation condition.

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