

## STUDY OF HEAT AND MASS RECOVERY PROCESS ON THE PERFORMANCE OF ADSORPTION COOLING SYSTEMS

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### ABSTRACT

A double-bed adsorption cooling system with silica gel as adsorbent and water as adsorbate was developed and tested and various operating sequence have been tried. The experimental results show that heat recovery cycle will increase the coefficient of performance (COP) and specific cooling power (SCP) by about 41.2% and 15.1%, respectively if compared with basic cycle. Besides, the results also indicated that mass recovery cycle can help to enhance the cooling performance of the adsorption cooling systems as well. The COP and SCP were enhanced to 0.25 and 67.7 W/kg, which were improved by about 47.1% and 40.5% respectively comparing to the basic cycle. The optimized operation sequence for this adsorption cooling system prototype is heat recovery of 37 seconds and mass recovery of 23 seconds. The COP and SCP under this optimized sequence were recorded at 0.34 and 75 W/kg, respectively, which were about 100% and 55.6% increase comparing to the basic cycle.

### INTRODUCTION

Thermal systems contribute to significant amount of electricity consumption in buildings. Traditional vapor compression systems utilize HCFCs or HFCs as refrigerants, and many of them have strong ozone depletion and global warming potential. Adsorption cooling systems can be an environmentally friendly alternative for traditional vapor compression systems used in buildings. Adsorption cooling systems require a low-grade thermal energy source with little electricity requirement for other system components [1-5]. Integrating adsorption cooling systems with solar energy or waste heat can substantially reduce the dependence on fossil fuels making them potential candidates for net zero energy building operation [6-10]. The adsorption cooling system utilizes the adsorption process of adsorbate on adsorbent to provide cooling effect, and the adsorbent will be saturated with the adsorbate after adsorption. Thermal energy from solar and

waste heat is then used to desorb the adsorbate out from the adsorbent for the next adsorption phase. Unlike traditional vapor compression cooling system, the production of cooling in adsorption cooling system is intermittent. Thus, at least two adsorbers filled with adsorbents have to be used in order to produce quasi-continuous cooling effect [11-15]. In operating the adsorption system, both pressure and temperature in the adsorbers will be changed between adsorption and desorption phases. If the switching between adsorption and desorption phase is not well controlled, large amount of energy will be wasted and the cooling production will be reduced [16-19].

In this study, heat recovery and mass recovery were investigated for improving the overall performance of the adsorption cooling systems. Performance tests were conducted under different operation sequences in a lab scaled dual-adsorbers prototype, and coefficient of performance (COP) and specific cooling power (SCP) are the major figure of merits. The cooling capacity and COP were determined experimentally. The adsorbent-adsorbate working pair used was silica-gel and water. The system performances with heat and mass recovery were compared to that with the basic cycle, where only adsorption and desorption phases were carried out. The importance of operation sequence control in adsorption cooling system was studied experimentally in this paper.

### NOMENCLATURE

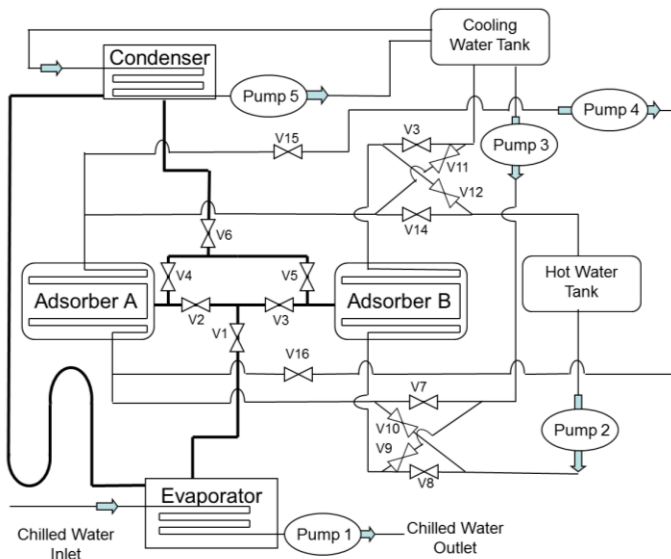
|               |          |                                    |
|---------------|----------|------------------------------------|
| $C_{p,water}$ | [J/kgK]  | Specific heat capacity of water    |
| COP           | [-]      | Coefficient of performance         |
| $\dot{m}$     | [kg/min] | Heat transfer 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 of silica gel                 |

Subscripts

|             |                                    |
|-------------|------------------------------------|
| <i>ads</i>  | adsorption                         |
| <i>chw</i>  | chilled water                      |
| <i>cond</i> | condenser/condensation             |
| <i>cool</i> | cooling water in adsorber/desorber |
| cycle       | cycle                              |
| <i>des</i>  | desorption                         |
| <i>eva</i>  | evaporator/evaporation             |
| hot         | hot water                          |
| in          | inlet                              |
| out         | outlet                             |

**WORKING PRINCIPLE OF THE ADSORPTION COOLING SYSTEM**

The basic cycle of operating the double-bed adsorption cooling system consists of two phases. In phase I, adsorption takes place in adsorber A, and desorption takes place in adsorber B. In phase II, desorption takes in adsorber A, and adsorption takes place in adsorber B. A schematic diagram of the adsorption cooling system is shown in Figure 1. The thinner lines represent the water pipeline for heating and cooling the adsorbers, while the thicker lines represent the low pressure pipeline for water vapour or condensed water.

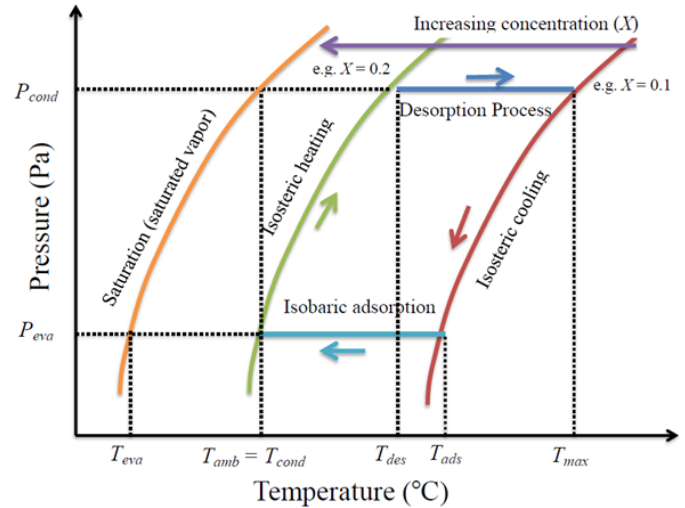


**Figure 1.** Schematic diagram of the adsorption cooling system

**Basic operation phases of the adsorption cooling systems**

In phase I, valves V1, V2, V5, V6, V7, V8, V11 and V12 are opened, while the other valves remain closed. In the adsorption-evaporation process, water in the evaporator 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 silica gel in Adsorber A, where cooling water removes the adsorption heat,  $Q_{ads}$ , generated. 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, which removes the latent heat,  $Q_{cond}$ . The condensed water comes back to the evaporator via the U-tube connecting the condenser and evaporator to

complete the cycle [4, 6, and 7]. By switching between Phase I and Phase II, a quasi-continuous cooling effect is produced. An isostere diagram is shown in Figure 2 for a better and clear explanation of the working principle of the adsorption cooling systems. In phase II, it is similar to the phase I, but the adsorber A is heated to desorb and adsorber B is cooled to adsorb. Thus, valves V1, V3, V4, V6, V9, V10, V13 and V14 are opened while the other valves remain closed.



**Figure 2.** Adsorption cycle in an isostere diagram

**Heat recovery process**

After desorption phase, the temperature of the corresponding adsorber is high, while another adsorber is cooled after adsorption phase. The heat recovery can recover some thermal energy from the heated adsorber to the cooled adsorber during phase switching between adsorption and desorption. The heat transfer fluid (water) flows through two adsorbers to transfer the heat from the heated adsorber to the cooled adsorber. By circulating the heat transfer fluid between the two adsorbers adiabatically, the energy efficiency can be increased significantly [14, 17, 18 and 20]. Valves V15 and V16 are opened while the other valves remain closed for operating the heat recovery cycle.

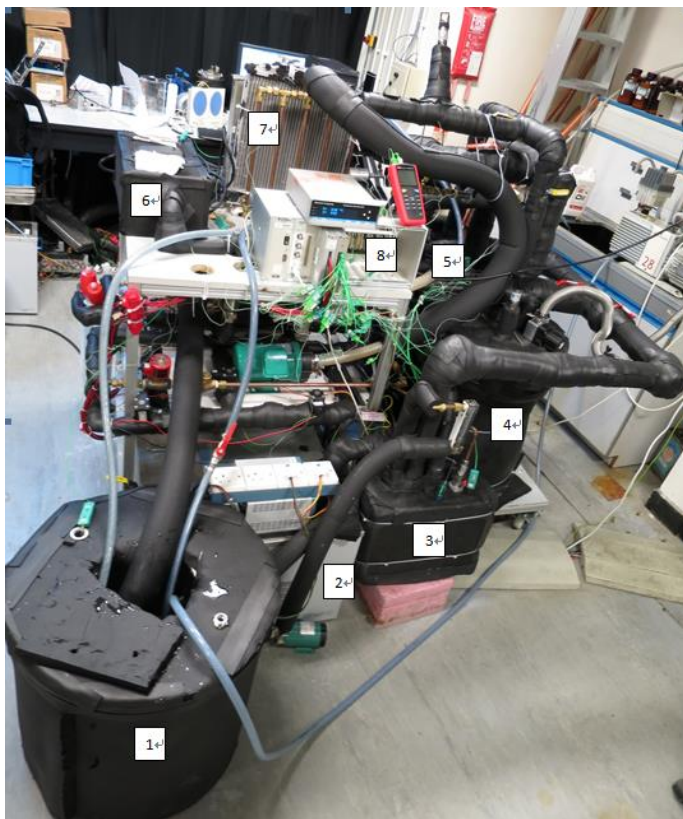
**Mass recovery process**

For operating the mass recovery, valves V2, V3, V4 and V5 are opened while the other valves remain closed. In this cycle, no adsorbers are connected with the evaporator or condenser. In the beginning of mass recovery, the heated adsorber has high pressure while the cooled adsorber has low pressure. The pressures are equal to those in either Phase I or Phase II. In Phase I or Phase II, the cooled adsorber is connected with the evaporator. Therefore, the pressure of the cooled adsorber is equal to that of the evaporator. Similarly, the pressure of the heated adsorber is equal to that of the condenser. By connecting two adsorbers together, the water vapour will flow from the high pressure heated adsorber to the low pressure cooled adsorber. Because of the pressure differences in the adsorbers, adsorption/desorption process will occur automatically without

any heating and cooling applied. Thus, the desorbed water vapor from heated adsorber will move to the cooled adsorber. The mass recovery can further dry the heated adsorber after desorption and reduce the pressure inside. The dryer adsorber can adsorb more water vapour in the next adsorption phase. The process will lead the adsorption cooling system to provide better performance [1, 12, 14 and 16-19].

## DESCRIPTION OF THE ADSORPTION COOLING SYSTEM PROTOTYPE

The photograph of experimental adsorption cooling system prototype was shown in Figure 3. The adsorption cooling system consisted of three water tanks. They were hot water tank (6) for the desorption purpose, cooling water tank (1) for removing the heat generated due to adsorption (heat of adsorption), and evaporator (3). The adsorption cooling system also had two adsorbers, adsorber A (4) and adsorber B (5). There was a condenser (7) at the top part, two adsorbers at the right, one evaporator at the bottom. An isothermal water circulator (2) was used to control the chilled water inlet temperature. All valves were controlled by the LabVIEW signal conditioning system (8).



**Figure 3.** A prototype of the adsorption cooling system [1: Cooling water tank; 2: Isothermal water circulator; 3: Evaporator; 4: Adsorber A; 5: Adsorber B; 6: Hot water tank; 7: Condenser; 8: LabVIEW signal conditioning system.]

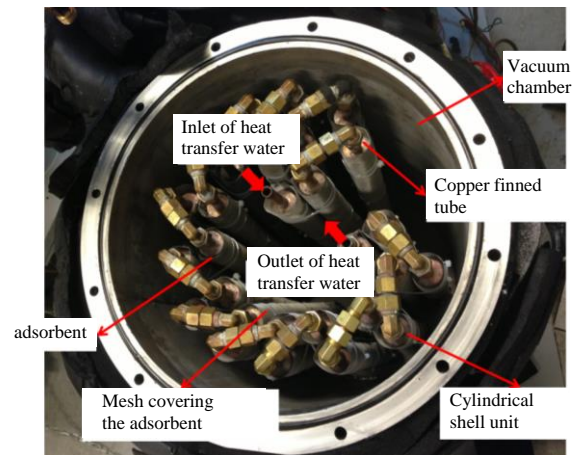
Circular finned tube design was utilized in the adsorbers, and silica gel was packed between the fins. Total weight of the silica gel adsorbent for each adsorber was 9 kg. A photograph

of an adsorber was shown in Figure 4. 14 cylindrical shell units were placed in a vacuum chamber to form an adsorber. Water from hot water tank and cooling water tank can flow into the adsorber through the inlet of heat transfer water. Inlet temperature of hot water was adjusted by heaters in the hot water tank while inlet temperature of chilled water was adjusted by an isothermal water circulator. Cooling water flows through an air-cooled heat exchanger to the adsorber and condenser, and then returns to the cooling water tank. Hot, cooling and chilled water flow rate were controlled manually, and monitored by rotameters. Temperatures of components including evaporator, adsorbers, condensers, water tanks, and inlet and outlet of water tanks were measured every 5 seconds by thermocouples. The pressures in evaporator, adsorbers and condenser were also measured. 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 was included in the calculation. The energy loss was mainly from the adsorbers, hot and cooling water tanks, piping system which heat transfer water was circulated, and heat capacities of the metal and heat transfer water. The performance of the prototype was investigated experimentally at a typical operation condition as shown in Table 1. The specific cooling power (SCP) of the system is expressed by

$$SCP = \frac{\dot{m}_{chw} C_p \text{ water} \int_0^{t_{\text{cycle}}} (T_{chw \text{ in}} - T_{chw \text{ out}}) dt}{W t_{\text{cycle}}} \quad (1)$$

The thermal COP is defined by the following equation

$$COP = \frac{\dot{m}_{chw} C_p \text{ water} \int_0^{t_{\text{cycle}}} (T_{chw \text{ in}} - T_{chw \text{ out}}) dt}{\dot{m}_{hot} C_p \text{ water} \int_0^{t_{\text{cycle}}} (T_{hot \text{ in}} - T_{hot \text{ out}}) dt} \quad (2)$$



**Figure 4.** 14 cylindrical shell units in a large vacuum chamber (adsorber)



**Table 1.** A typical operating condition for the adsorption cooling system

| Parameters                       | Symbol           | Value | unit   |
|----------------------------------|------------------|-------|--------|
| Hot water inlet temperature      | $T_{hot,in}$     | 85    | °C     |
| Hot water mass flow rate         | $\dot{m}_{hot}$  | 7     | kg/min |
| Cooling water inlet temperature  | $T_{cool,in}$    | 27    | °C     |
| Cooling water mass flow rate     | $\dot{m}_{cool}$ | 8     | kg/min |
| Chilled water inlet temperature  | $T_{chw,in}$     | 14    | °C     |
| Chilled water mass flow rate     | $\dot{m}_{chw}$  | 1.6   | kg/min |
| Adsorption/desorption phase time | $t_{cycle}$      | 15    | mins   |

## RESULTS AND DISCUSSIONS

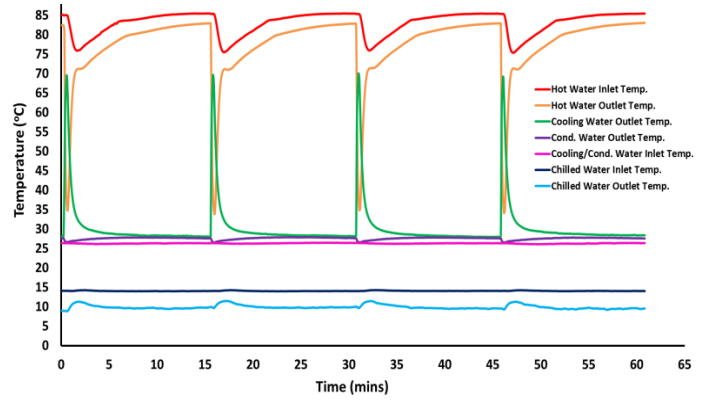
Before studying the effect of heat and mass recovery cycle, the basic cycle was investigated to obtain the reference performance of the system for fair comparisons. The varied operating sequence for the adsorption cooling system was shown in Table 2. Basic cycle, heat recovery cycle, mass recovery cycle, and heat and mass recovery cycle were included. The desorption temperature was set to be 85 °C. The cooling water inlet temperature supplying to the adsorbers was controlled at 27°C; while the evaporating temperature was set to be 14°C by the isothermal water circulator. The adsorption/desorption phase time was 15 minutes. The heat transfer fluid mass flow rate for the hot water and cooling water was set to be 7 kg/min and 8 kg/min, respectively. And, the mass flow rate for the chilled water was 1.6 kg/min. This typical operating condition was the same for running four different sequences as shown in Table 2.

**Table 2.** Varied operating sequence for the adsorption cooling system [I: Phase I; II: Phase II; HR: Heat Recovery; MR: Mass Recovery; HMR: Heat & Mass Recovery]

| Operating Sequence Options   |                             |
|------------------------------|-----------------------------|
| Basic Cycle                  | I → II → ....               |
| Heat Recovery Cycle          | I → HR → II → HR → I ....   |
| Mass Recovery Cycle          | I → MR → II → MR → I ....   |
| Heat and Mass Recovery Cycle | I → HMR → II → HMR → I .... |

### Basic cycle performance

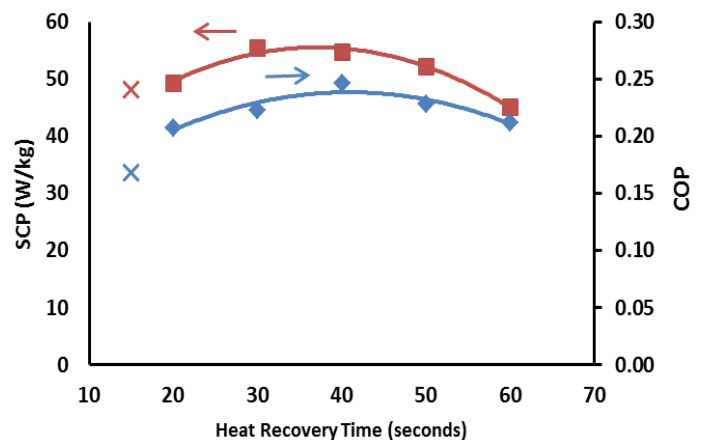
Using the basic cycle for the adsorption cooling system with the operating condition as presented in Table 1, the COP and SCP were calculated to be 0.17 and 48.2 W/kg, respectively. The experimental temperature profiles of the heat transfer fluid inlets and outlets in different locations were shown in Figure 5. It was shown that the delivered chilled water outlet temperature was always below the inlet temperature throughout the whole cycle, indicating that the cooling process was steady and successful in producing the cooling effect. The difference in chilled water temperature was averagely about 4 °C. Large variations of outlet temperatures were observed during the transition between Phase I and Phase II. This indicated the thermal energy from the heated adsorber was wasted, and can be recovered by heat recovery process.



**Figure 5.** Experimental heat transfer fluid temperature profiles of basic cycle

### Effect of heat recovery on the SCP and COP

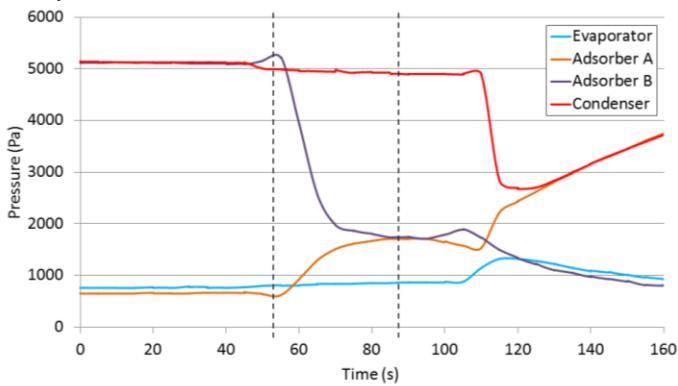
The effect of heat recovery to the performance of the adsorption cooling system is discussed in this section. As the heat recovery phase time is the most important parameter, different heat recovery phase time was set to study the effect of heat recovery. From Figure 6, it can be seen that longer heat recovery phase time might not give the highest value of SCP and COP. This is because of the relatively larger heat loss for a longer heat recovery phase time. Besides, there was no cooling effect produced during the heat recovery phase. In another word, a longer heat recovery time diminished the cooling performance of the adsorption cooling systems. The SCP and COP value were also low when the heat recovery cycle time was short. This is because the heat was not effectively and completely recovered at the short heat recovery phase time, resulting in a poor SCP and COP. Therefore, there exists the best heat recovery cycle time which is around 37 seconds for this adsorption cooling system prototype, and under this heat recovery process time, the COP and SCP were recorded at about 0.24 and 55.5 W/kg, respectively.



**Figure 6.** Effect of heat recovery time on the SCP and COP [Red cross: SCP of basic cycle; Blue cross: COP of basic cycle]

### Effect of mass recovery cycle on the SCP and COP

As mentioned before, the pressure of the heated adsorber at the end of the desorption phase is higher than the cooled adsorber at the end of the adsorption phase. After that, the high pressure adsorber needs to be cooled down and depressurized while the low pressure one needs to be heated up and pressurized for the next phase. The two adsorbers was interconnected directly by opening valves V2, V3, V4 and V5, and the water vapor can flow from the high-pressure adsorber to the low pressure one. The pressure of the heated adsorber decreased due to the outward water vapour flow and this caused further desorption of the adsorbent. Meanwhile, the pressure of the cooled adsorber increased due to the inward water vapour flow and caused further adsorption. The process was conducted until the two adsorbers reached the same pressure. The pressure variation was shown in Figure 7. The mass recovery phase time was set to be 35 seconds so the variation can be seen more clearly.

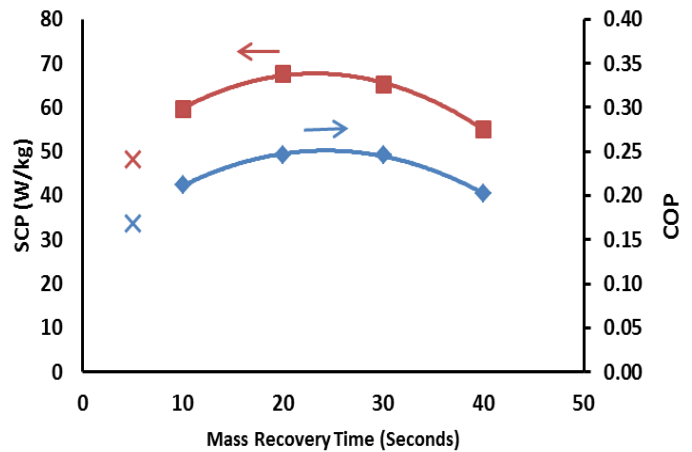


**Figure 7.** Pressure Variation of components during mass recovery for 35 seconds

Then the valves were closed and the adsorbers were ready for the next phase. The mass recovery process was expected to accelerate the circulation and enhance the cycle cooling power [1, 12, 14 and 16-19], as it only involved direct mass flow and the pressure balance is much faster than temperature balance (heat recovery process) via heat-transfer medium.

Figure 8 showed the effect of mass recovery process time on the SCP and COP of the adsorption cooling system. Similar to the heat recovery cycle time influence, mass recovery phase time also shows a peak for both SCP and COP. The peak is at around 23 seconds and this is the best mass recovery time for the adsorption cooling system prototype. The longer the mass recovery time, the poorer the cooling performance of the adsorption cooling system is. This is because no cooling effect is actually produced during the mass recovery process. This implies to have a shorter mass recovery time. However, a shorter mass recovery time might not give a better cooling performance due to an incompletely mass recovery cycle. As a result, there exists an optimum value of the mass recovery cycle time. Under this mass recovery phase time, the COP can be approached to 0.25; while the SCP was recorded at 67.7 W/kg. It should be noted that these COP and SCP values recorded does not involve any heat recovery cycle, and only mass recovery cycle is included during the phase change. Therefore,

a combined heat and mass recovery cycle influence was studied accordingly to optimize the system performance.



**Figure 8.** Effect of mass recovery time on the SCP and COP [Red cross: SCP of basic cycle; Blue cross: COP of basic cycle]

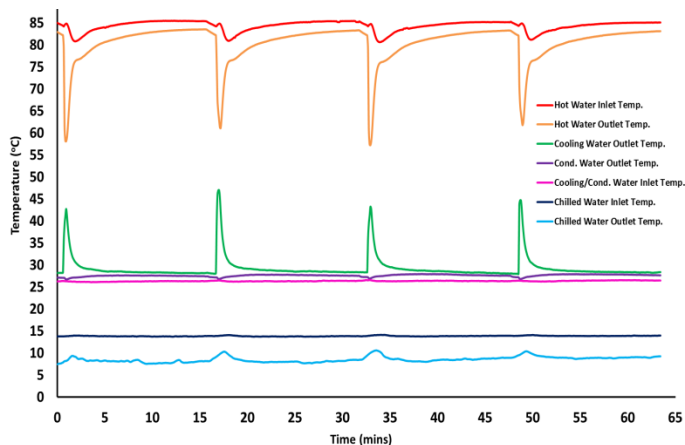
### Effect of heat and mass recovery cycle on the SCP and COP

In this section, a combined heat and mass recovery cycle is studied. As discussed previously, the best duration for heat and mass recovery cycle time is about 37 seconds and 23 seconds, respectively. Thus, these values were adopted to perform heat and mass recovery. In details, heat and mass recovery process were begun at the same time after either Phase I or Phase II for the first 23 seconds. After 23 seconds, the mass recovery process was stopped while heat recovery was conducted for 14 seconds more. A combined heat and mass recovery cycle was performed by this sequence. The results were presented in Table 3. It was found that performing heat recovery cycle can help to enhance both COP and SCP, but the enhancement of COP is more significantly than that of the SCP. So, it could be concluded that heat recovery cycle is more effective to the COP enhancement for the adsorption cooling systems. Regarding the mass recovery cycle, SCP and COP were improved by about 40.5% and 47.1%, respectively. The improvements are quite close with each other after conducting mass recovery cycle. Thus, mass recovery cycle can help to enhance both SCP and COP of the adsorption cooling systems. However, the improvement is not that significantly when it is compared with heat and mass recovery combined cycle. Based on the experimental result obtained, performing heat and mass recovery at the same time, the COP was increased by almost 100%; while the SCP can also be enhanced by about 55.6% comparing to that of the basic cycle. The improvement was very significant and proved that heat and mass recovery is very effective in improving the system performance. Without changing any components of the adsorption cooling system, and just performing 37 seconds of the heat recovery and at the same time 23 seconds of the mass recovery, the COP was doubled and the SCP was increased by 55.6% compared to the basic cycle without performing any heat and mass recovery. Thus, performing heat and mass recovery cycle during the phase change is very important and it benefits a lot to the cooling performance of the adsorption cooling systems.

**Table 3.** Comparison with basic cycle

| Operating Sequence     | COP  | COP $\Delta\%$ | SCP (W/kg) | SCP $\Delta\%$ |
|------------------------|------|----------------|------------|----------------|
| Basic cycle            | 0.17 | N.A.           | 48.2       | N.A.           |
| Heat recovery only     | 0.24 | 41.2%          | 55.5       | 15.1%          |
| Mass recovery only     | 0.25 | 47.1%          | 67.7       | 40.5%          |
| Hand and mass recovery | 0.34 | 100.0%         | 75.0       | 55.6%          |

Moreover, a temperature profile of heat transfer water with the heat and mass recovery being conducted was shown in Figure 9. Comparing to Figure 5, it was clearly shown that some heat was recovered during the phase change. In Figure 5, hot water and cooling water outlet temperature increased or decreased a lot during the phase change process since no heat recovery process was performed. This indicated that a large amount of heat had to be transferred in and out from the adsorbers. This lowers the desorption temperature which implies that a longer desorption time is required in order to completely dry the adsorbent. This also lowered the cooling capacity of the adsorption cooling systems because the temperature of the adsorber was high. On the other hand, it is shown in Figure 9 that the temperature variation of hot water outlet and cooling water outlet are smaller since some heat was recovered in heat recovery process. As a result, the cooling performance (i.e. COP and SCP) of adsorption cooling systems was hugely enhanced.



**Figure 9.** Experimental heat transfer fluid temperature profiles of combined heat and mass recovery cycle

## CONCLUSION

There is an increasing need for energy efficiency and requirement for the system driven with low temperature heat sources. For the realization of this demand, a double-bed silica gel – water adsorption cooling system with heat and mass recovery cycle were presented and the effects of operating sequences were investigated. At the same operating condition, heat recovery cycle, mass recovery cycle, and heat and mass

recovery cycles have advantages over the basic cycle. The followings are the conclusions made based on this study:

1. Only performing the heat recovery cycle, the COP can be improved a lot comparing to the SCP. So, heat recovery cycle is more effective to the COP enhancement of the adsorption cooling systems.
2. Only performing the mass recovery cycle, both SCP and COP can be improved, and the improvement is about 40.5% and 47.1%, respectively comparing to that of the basic cycle.
3. No matter performing which recovery cycles (heat or mass recovery cycle), the effect is not that significant when it is compared to perform both heat and mass recovery cycle together at the same time. The COP was recorded at 0.34 which was improved by about 100%. And, the SCP was obtained at about 75 W/kg which was enhanced by about 55.6% comparing to that of the basic cycle. Thus, it can be concluded that heat and mass recovery cycle has a huge improvement on the COP and SCP of the adsorption cooling systems, and it is highly recommended to conduct the heat and mass recovery process during the phase change.
4. In order to obtain an optimal heat and mass recovery cycle's performance, an appropriate heat and mass recovery time should be selected. 37 seconds is the best heat recovery phase time for this adsorption cooling system prototype; while 23 seconds is the best one for the mass recovery phase time. The ratios to the adsorption phase time are 0.041 and 0.026 respectively.

## ACKNOWLEDGEMENT

Funding sources for this research are provided by the Hong Kong Research Grant Council via General Research Fund account 611212.

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