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Research on a compact adsorption room air conditioner

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Abstract

A novel compact adsorption room air conditioner with a cooling capacity of 1 kW has been designed, and two prototypes have been built. A two bed, continuous adsorption refrigeration cycle with heat recovery and mass recovery is adopted. Micropore spherical silica gel and water are selected as the working pair. A gravity heat pipe with methanol as working medium is designed to output the cooling. Experimental investigations have indicated that under typical air conditioning conditions, for the first prototype, a cooling capacity of 687 W and a COP (coefficient of performance) of 0.307 can be obtained. However, for the improved one, a cooling capacity of 790 W and a COP of 0.446 can be reached. It is also proved that the operating temperatures have strong influences on the performance. The designed room air conditioner can be driven by a low grade heat source (<90 °C) and has small dimensions of 300 mm (depth), 500 mm (width) and 950 mm (height).

Keywords: Adsorption refrigeration; Room air conditioner; Silica gel; Waste heat; Low grade; Thermal energy

1. Introduction

Adsorption refrigeration technology is an environmentally friendly technology in which natural and environmentally benign substances such as water, methanol, ammonia, etc. are adopted as refrigerants. In the last two decades, with increasing concern about energy availability and environmental protection, adsorption refrigeration technology has been gaining more and more attention, and different types of adsorption systems and prototypes have been developed and studied [1].

In 1987, Yonezawa et al. developed and commercialized a silica gel–water adsorption chiller [2,3]. In the chiller, a two bed continuous cycle with heat recovery process was adopted, and finned heat transfer tubes were introduced as adsorption units. Silica gel particles were packed around the finned heat transfer tubes and fixed by wire mesh. Experimental researches on the chiller had shown that for a cycle time of 450 s, a

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cooling output of 10.30 kW and a COP of 0.34 could be obtained with a hot water inlet temperature of 85 °C, a cooling water inlet temperature of 30 °C and a chilled water inlet temperature of 14 °C [4]. No mass recovery process was included in the chiller.

The silica gel–water adsorption refrigeration system has been investigated systematically by Saha [5–9]. To utilize low grade waste heat, Saha et al. introduced a three stage adsorption cycle that could be driven by waste heat of 50 °C in combination with a heat sink of 30 °C [6]. Though the cooling output and COP are not so exciting, considering that the driving energy comes from waste heat, the cycle is worthy of further study. Saha et al. built a two stage non-regenerative adsorption chiller that could be operated effectively with 55 °C solar energy/waste heat in combination with a 30 °C coolant inlet temperature [7].

For a conventional two bed continuous cycle, the highly dynamic adsorption rate results in fluctuations of the cooling output and the cooling load of the condenser. The cooling output fluctuation, which will result in fluctuation of the chilled water outlet temperature, is not welcome in some occasions. When a cooling tower is used to supply the cooling water, the fluctuation of the cooling load of the condenser will cause variation of the cooling water inlet temperature. To improve the conditions, a multi-bed adsorption refrigeration cycle has been introduced and investigated [8,9]. At any time, there is more than one adsorber undergoing the adsorption (desorption) phase, and thus, the cooling load of the condenser and the heating load of the evaporator can be adjusted automatically. Thus, the rapid increase (decrease) of the loads can be avoided. Besides, Saha et al. also introduced a dual mode, multi-stage, multi-bed regenerative adsorption system [10]. The system operates in the multi-stage, two bed mode when the hot water inlet temperature is less than 60 °C and in the single stage, multi-bed mode when higher hot water inlet temperature can be obtained.

Heat and mass recoveries can improve the performance of an adsorption system effectively. R.Z. Wang has thoroughly investigated the influences of heat and mass recoveries on the performance of adsorption systems and has also performed comparisons with conventional adsorption cycles [11]. The influences of the degrees of heat and mass recoveries on adsorption system performance have been studied by Wang [12].

An adsorption heat pump system with heat recovery was studied by Wu et al. [13] in which a novel shell-tube exchanger structure was adopted as the adsorption heat exchanger. Gui et al. conducted experimental researches on the dynamic characteristics of a heat regenerative adsorption air conditioning system [14]. To increase the cooling output, Alam et al. introduced a mass recovery process into a four bed adsorption cycle [15]. It was shown that the cooling output of the system was higher than that of a two stage system for regeneration temperatures higher than 70 °C.

During the past several years, the research group of R.Z. Wang has systematically studied various adsorption refrigeration cycles with heat and mass recoveries and built some adsorption chiller prototypes [16].

In comparison with absorption refrigeration, adsorption refrigeration systems have the superiority in the smaller cooling capacity range (for example, $\leqslant$100 kW). There are already a lot of researches and products of silica gel–water adsorption chillers, however, no scale of 1 kW has been studied. In this paper, a compact adsorption room air conditioner with a cooling capacity of 1 kW is designed and fabricated, and experimental researches are also conducted. To use low temperature driving energy, silica gel and water are chosen as the adsorption pair.

2. Design of the prototype

For traditional two bed adsorption refrigeration systems, there is always a vacuum valve between the adsorber and condenser (evaporator). The valve between the adsorber and condenser is opened when the pressure in the adsorber increases to that in the condenser at the beginning of the desorption process and closed at the end of the desorption process. Similarly, the valve between the adsorber and evaporator is opened when the pressure in the adsorber decreases to that in the evaporator at the beginning of the adsorption process and closed at the end of the adsorption process. For a real adsorption refrigeration system, the time interval of one cycle is usually in several tens of minutes. Thus, the vacuum valves must be opened and closed frequently. So, they are often damaged, which reduces the reliability of adsorption refrigeration systems.

For the adsorption air conditioner proposed in this paper (Fig. 1), we think the reliability is vitally important. Therefore, in our design, we enclose one adsorber, one water condenser and one water evaporator (located from the upper to lower) in one vacuum chamber (adsorption/desorption working chamber), and then, no vacuum

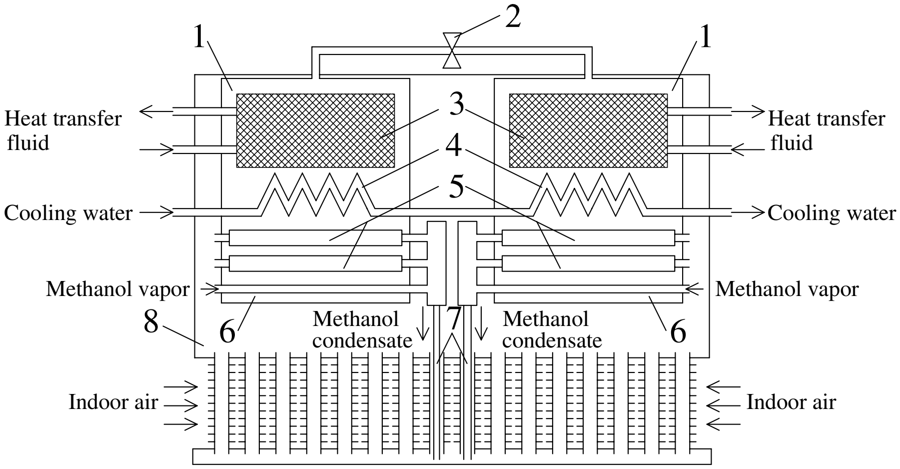

Fig. 1. Schematic diagram of the compact adsorption room air conditioner. 1. Adsorption/desorption working chamber, 2. electromagnetic vacuum valve, 3. adsorber, 4. water condenser, 5. water tray, 6. water evaporator (methanol condenser), 7. methanol condensate return tube, 8. heat pipe working chamber.

valve is needed between the adsorber and the water condenser or the water evaporator. Compared to conventional designs, this novel design can improve the reliability of adsorption refrigeration systems remarkably.

The adsorber (5 kg silica gel in each) has a tube integrated fin structure, and silica gel is packed between the fins. Mass transfer channels are designed between the heat transfer channels. The outer diameter of the heat transfer tubes is 9.52 mm and that of the mass transfer channels is 12 mm. The maximum heat and mass transfer distances in the adsorber are 1.25 mm and 12.5 mm, respectively. The total heat transfer area on the silica gel side is 3 m^2. A photo of the adsorber is given in Fig. 2.

For the water condenser, a tube-shell structure is adopted, and the shell is also the wall of the adsorption/desorption working chamber. The outside heat transfer area of the water condenser is 0.21 m^2. The water condenser is located over the water evaporator, so the water condensate will flow downwards into the water evaporator directly. The water evaporator (Fig. 3) is also a tube-shell heat exchanger, and the shell is also the wall of the adsorption/desorption working chamber. The heat transfer tubes in the water evaporator have enhanced outside surfaces. When the water evaporates, the tubes are not immersed in the water completely. Thus, some water will flow upwards to the top surfaces of the tubes by capillary force, which will form a thin liquid film. So, the heat transfer of the water evaporator can be enhanced. There are three rows and four columns of heat transfer tubes in the water evaporator, and under each row of tubes, one water tray is designed.

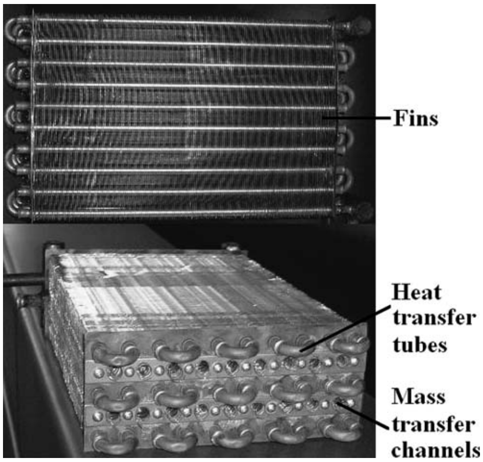

Fig. 2. A photo of the adsorber.

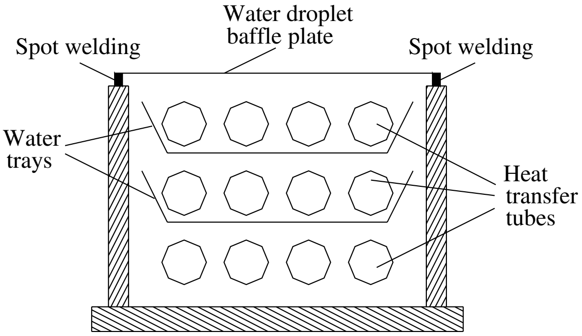

Fig. 3. Water evaporator schematic diagram.

There are two such adsorption/desorption working chambers in the adsorption air conditioner. To perform the mass recovery process, an electromagnetic valve is used to connect the two adsorption/desorption working chambers.

For the proposed adsorption air conditioner of 1 kW cooling output, one critical thing is that such small cooling output is not suitable to be transferred by pumping chilled water through fan coils and should be output to the space directly, simply by a small fan (several tens of Watts). In the adsorption air conditioner, there are two water evaporators. When the water in one water evaporator evaporates, the water in the other one is at the condensation temperature. For the indoor air, the switch from one water evaporator to the other needs two valves. For bigger volume flow rate of the blowing air, the two valves are very big in volume. Moreover, more valves will do harm to the system reliability. To improve the system reliability and reduce the prototype volume, a gravity heat pipe with methanol as working medium is designed to output the cooling. The working space of the gravity heat pipe is also a vacuum chamber (heat pipe working chamber) that surrounds the two adsorption/desorption vacuum chambers. The hot end of the gravity heat pipe (methanol evaporator) adopts a tube-fin structure, and the cold end (methanol condenser) outside surface is also the water evaporating surface of the water evaporator.

When the indoor air blows (driven by a fan of 20 W) on the methanol evaporator, the methanol inside evaporates, and then, the methanol vapor condenses in the methanol condenser. The methanol condensate flows downwards into the bottom of the methanol evaporator through a specially designed passage.

To control the flows of the hot water and cooling water, 11 electric valves are used. All the valves used in the air conditioner are controlled by a PLC controller.

The compact adsorption room air conditioner is designed with a cooling capacity of 1 kW, and the design dimensions are 300 mm (depth) × 500 mm (width) × 800 mm (height).

3. Working principle and control strategy

Based on the studies of the research group of R.Z. Wang in recent years [11,12], heat and mass recovery processes can improve the performance of adsorption refrigeration systems greatly. So, a two bed continuous cycle with heat and mass recoveries is adopted for the proposed air conditioner. The *p–T–x* diagrams for the ideal basic cycle and the ideal cycle of the proposed adsorption air conditioner are given in Fig. 4. A whole cycle process for the air conditioner can be described as follows:

(1) The left adsorber (see Fig. 1) works in the adsorption phase (D–A in Fig. 4), and the right adsorber works in the desorption phase (B–C in Fig. 4). During the process, the cooling and hot waters flow through the left and right adsorbers, respectively. The water vapor evaporated from the left water evaporator is adsorbed by the left adsorber, and the water vapor desorbed by the right adsorber is condensed in the right water condenser. The water condensate flows downwards into the right water evaporator directly. The methanol vapor evaporated from the methanol evaporator is condensed in the left methanol condenser (the left water evaporator), and then, the methanol condensate flows downwards into the bottom of the methanol evaporator.

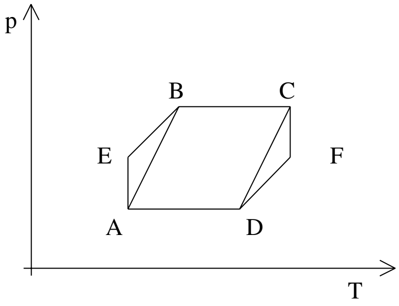

Fig. 4. *p–T* diagrams for ideal basic cycle and ideal cycle of the air conditioner.

(2) Mass recovery process from the right adsorption/desorption working chamber to the left one (C–F and A–E in Fig. 4). During the process, the two adsorption/desorption working chambers are connected by the electromagnetic valve. Then, the pressure decreases in the right chamber and increases in the left chamber. When the pressures in the two chambers reach nearly the same, the electromagnetic valve is closed, and the process stops.

(3) Heat recovery process from the right adsorber to the left adsorber (F–D and E–B in Fig. 4). During the process, the hot water is bypassed, and the cooling water flows through the right adsorber. The cooling water flowing out of the right adsorber is used to heat the left adsorber and then returns to a constant temperature bath or cooling tower.During the heat and mass recovery processes, the cooling output produced by the water evaporation is very small, but the cooling power of the air conditioner is not very low because of the sensible cooling stored in the water evaporators.

(4) The left adsorber works in the desorption phase (B–C in Fig. 4), and the right adsorber works in the adsorption phase (D–A in Fig. 4). During the process, the hot and cooling waters flow through the left and right adsorbers, respectively. The water vapor evaporated from the right water evaporator is adsorbed by the right adsorber, and the water vapor desorbed by the left adsorber is condensed in the left water condenser. The water condensate flows downwards into the left water evaporator directly. The methanol vapor evaporated from the methanol evaporator is condensed in the right methanol condenser (the right water evaporator), and then, the methanol condensate flows downwards into the bottom of the methanol evaporator.

(5) Mass recovery process from the left adsorption/desorption working chamber to the right one (C–F and A–E in Fig. 4).

(6) Heat recovery process from the left adsorber to the right adsorber (F–D and E–B in Fig. 4). During the process, the hot water is bypassed, and the cooling water flows through the left adsorber. The cooling water flowing out of the left adsorber is used to heat the right adsorber and then returns to a constant temperature bath or cooling tower.

The above six steps compose a whole adsorption refrigeration cycle.

Because there is no vacuum valve between the adsorber and the water condenser or the water evaporator, a fixed time control strategy is adopted for the air conditioner. Based on our previous experience and the advices provided by the factory, we chose 900 s, 180 s and 20 s for the adsorption (desorption) process and the mass and heat recovery processes, respectively. The adsorber is still connected to the heat transfer fluid during the mass recovery process, and thus, the mass recovery process is nearly an isothermal process. Because the adsorption and desorption processes are highly dynamic and non-equilibrium, the condensation and evaporation temperatures fluctuate all the time in a real system.

4. Performance test

A compact adsorption room air conditioner was designed and two prototypes were manufactured (for one prototype, see Fig. 5). The design cooling capacity is 1 kW under the typical air conditioning conditions given in Table 1. The evaluation test was conducted in the Enthalpy-difference room.

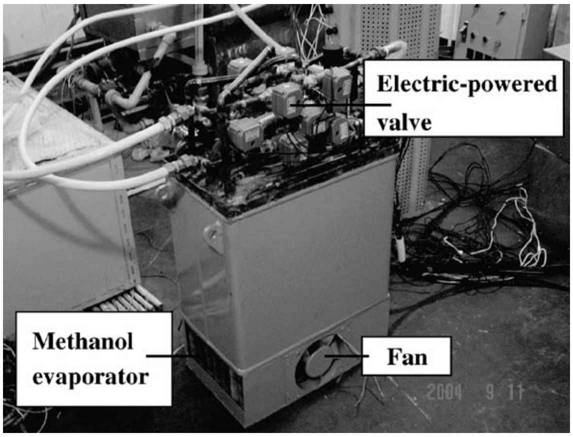

Fig. 5. Compact adsorption room air conditioner prototype.

Table 1
Typical air conditioning condition

Hot water	Cooling water		Air sucked
Flow rates (l/min)			
5	10		4500
Hot water inlet	Cooling water inlet	Indoor air dry bulb	Indoor air wet bulb
Temperatures (°C)			
85	30	27	19

4.1. Test set-up and measuring error

The Enthalpy-difference method set-up has an accuracy of ±2% for both measurement and repetitiveness. Hot water is supplied by a constant temperature hot water tank, and cooling water is supplied by a constant temperature cold water tank. The hot water tanks can control a temperature fluctuation to less than ±0.2 °C in the range of 70–85 °C, and also to less than ±0.2 °C for the cold water tank in the range of 25–35 °C. For temperature measurement, an accuracy of ±0.2 °C can be reached. For flow rate measurement and control, accuracies of ±0.5% and ±1% can be guaranteed, respectively. A photograph of the set up is shown in Fig. 6.

4.2. Test scheme

For an air conditioner or chiller, the cooling output and COP are the most important performance parameters. Many factors, such as operating temperatures, flow rates, cycle times, etc., can affect the parameters.

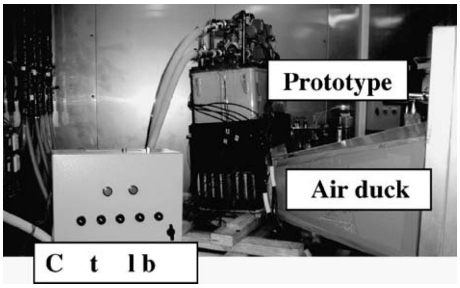

Fig. 6. Enthalpy-difference method set-up.

Table 2
Operating temperatures

Operating conditions		Hot water inlet (°C)				
		70	75	80	85	90
Cooling water inlet (°C)	28	○	○	○	○	○
	30	×	×	○	○	○
	32	×	×	○	○	○

(○) including; (×) excluding.

According to Saha [4], the flow rates of hot water and cooling water have stronger influences on the cooling output than that of chilled water. However, this is only true for small flow rates. When the flow rates of hot water and cooling water increase, the influence weakens quickly. It was also found that cycle times had little effect on the cooling output but had a positive effect on the COP. In this evaluation test, just the operating temperatures, namely the temperatures of the hot water inlet and the cooling water inlet, are changed. The aim was to obtain the performance of the prototype under the design working condition. The effects of the operating temperatures on the cooling output and COP are also what we want to study. Table 2 gives the operating temperatures in the experiment. The flow rate parameters are in accordance with those listed in Table 1. The cycle time is 38 min.

4.3. Test results and discussion

We have conducted experimental investigations on both the prototypes, and the following are the results of the first prototype. The results for the second one will be given later.

4.3.1. Temperature histories

Fig. 7 shows the experimental temperature histories of the hot water inlet $T_{hw,i}$, outlet $T_{hw,o}$ and the cooling water inlet $T_{cw,i}$. For the cooling water, the outlet temperatures of the adsorber $T_{cw,o,a}$ and water condenser $T_{cw,o,c}$ are given. From the figure, we can see that the heat flux decreases when the adsorber temperature increases in the desorption phase and decreases when the adsorber temperature decreases in the adsorption phase.

The heat and mass recovery processes have resulted in some interesting phenomena (Fig. 8). During the mass recovery, the two adsorption/desorption working chambers are connected. So, the pressure in the hot chamber decreases sharply, which causes the hot adsorber to desorb more gaseous adsorbate quickly. Thus, more heating load is needed. The hot water is bypassed during the heat recovery, and therefore, $T_{hw,o}$ equals

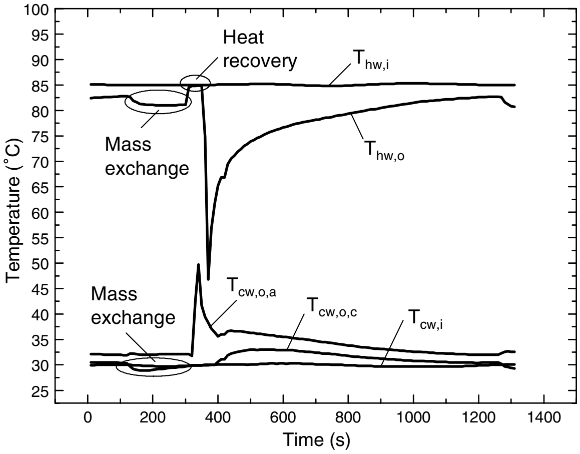

Fig. 7. Temperature histories for typical air conditioning condition.

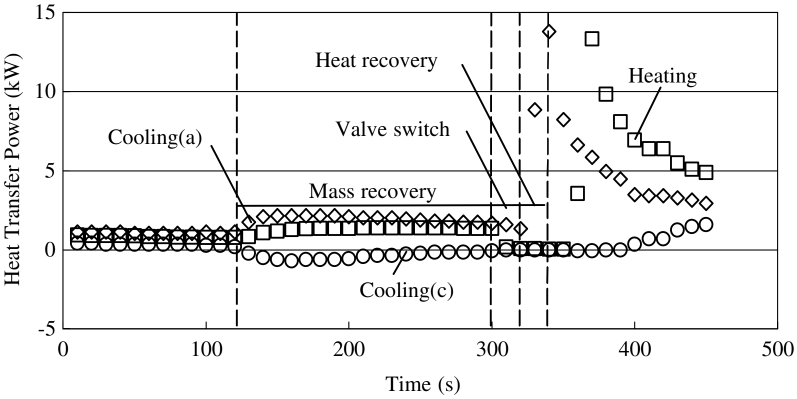

Fig. 8. Heat transfer powers versus operation time. Heating—heating load of the adsorber, cooling(a)—cooling load of the adsorber, cooling(c)—cooling load of the water condenser.

$T_{hw,i}$ at that time. From the cooling load curves, we can see that during the mass recovery, $T_{cw,o,c}$ is lower than $T_{cw,i}$, and the cooling load of the adsorber increases. Those are caused for the reasons:

(1) When desorbing, the outside surface of the water condenser is covered by a thin liquid film. During the mass recovery, due to the sudden decrease of pressure in the hot chamber, the liquid film evaporates, which absorbs some heat from the cooling water. Thus, the cooling water is cooled in the condenser.
(2) Near the end of the adsorption process, the cooling load of the adsorber becomes very small, but during the mass recovery, the pressure increase makes the adsorbent adsorb more gaseous adsorbate that needs more cooling to remove the adsorption heat. So, the cooling load of the adsorber increases.The temperatures of the air sucked, blowed and methanol evaporation are shown in Fig. 9.

During the heat and mass recoveries, the adsorption rate is very small, but from Fig. 9, we can see that the cooling output during the processes is not the case. The reason is that at the beginning of the mass recovery, the temperature in the methanol evaporator is still very low, and thus, the methanol can absorb much heat from the indoor air and some cooling can be produced. Therefore, the methanol temperature increases quickly during the processes. The heat transfer temperature difference between the indoor air and the methanol is higher (4–5 °C). That is caused by the water condensate staying on the outside surface of the methanol evaporator.

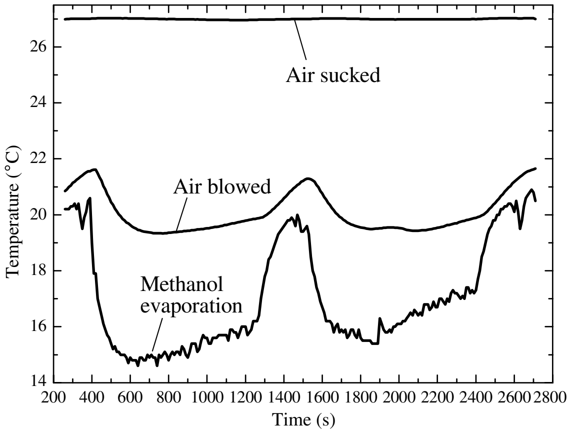

Fig. 9. Air sucked, air blowed, methanol evaporation temperatures and time.

4.3.2. Cooling output

Fig. 10 gives the transient cooling outputs of the air conditioner prototype. The variation is caused mainly by the variation of the adsorption rate. During the adsorption phase, the adsorption rate will experience a process of rapid increase, slow variation and then rapid decrease, as it is reflected from the cooling output curve. From the curve, we also can see that the slow variation phase lasts much longer than the other two phases and has high cooling output. Those are beneficial for a higher average cooling output.

4.3.3. Influence of operating temperatures on the average cooling output and COP

Figs. 11 and 12 give the values of COP and the average cooling output under different working conditions.

The air conditioner prototype can reach a maximum COP of 0.324 under the working condition of 85 °C and 30 °C for the hot water inlet and cooling water inlet temperatures, respectively. The COP value increases with the hot water inlet temperature until 85 °C and then decreases afterwards. The higher is $T_{hw,i}$, the bigger is cycle adsorption amount, but at the same time, the adsorber needs more sensible heat. So, there exists one optimum $T_{hw,i}$. From the figures, we can also know that the lower is $T_{cw,i}$, the higher is the COP that can be obtained.

Higher $T_{hw,i}$ and lower $T_{cw,i}$ are desired for the higher average cooling output because they both are beneficial to improve the cycle adsorption amount. The average cooling output increases with $T_{hw,i}$ quickly before

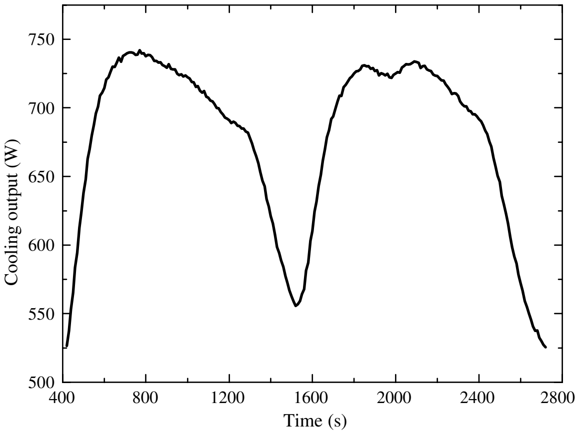

Fig. 10. Cooling output changes with time.

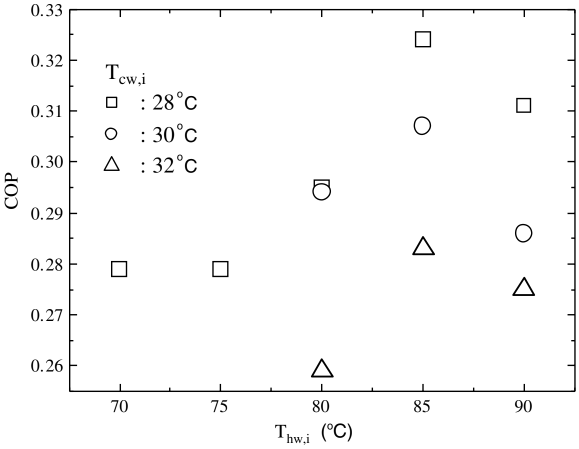

Fig. 11. Operating temperatures and COP.

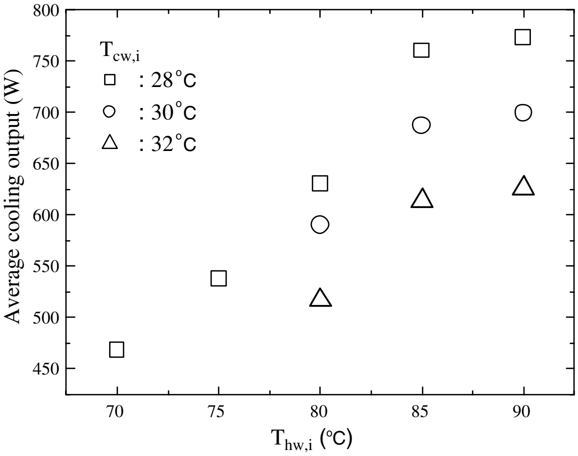

Fig. 12. Operating temperatures and the average cooling output.

85 °C but slowly after that. The reason is that when $T_{hw,i}$ exceeds 85 °C, the continuous increase of $T_{hw,i}$ has little effect on the increase of the cycle adsorption amount. For the cooling water, it can be found that the average cooling output increases sharply with the decrease of $T_{cw,i}$.

From the experimental data of the first prototype, we have found two problems:

(1) When flowing through the methanol evaporator, the indoor air is, sometimes, humidified.
(2) The evaporation temperatures on both sides of the methanol evaporator are not equal.

The first problem is caused by the unreasonable design of the fins of the methanol evaporator. The condensed water on the fins is difficult to remove. When the indoor air blows on the fins, on one hand, the air will be cooled down and some water vapor in the air will be condensed if the temperature of the air blowed is low enough, while on the other hand, some water condensate retained on the fin surfaces will also enter the air. Thus, when the temperature of the air blowed is not low enough, the water entering the air is more than that leaving, and the air will be humidified.

The second problem is caused by the manufacture. In the methanol vapor flow channel of the methanol evaporator, there are two liquid baffle plates on the left and right sides. One plate was damaged in the assembly, and thus, not only the methanol liquid can be baffled but also the methanol vapor can be baffled. So, the flow resistance on one side is higher than that on the other side, which has caused the evaporation temperature difference between the two sides.

We have built another prototype, and the test experiment has also been done. For the new prototype, we have improved the assembly accuracy and redesigned the methanol evaporator fins so the water condensate on the fins can be removed in time. For this prototype, we have just recorded the average cooling output and COP. The average cooling output and COP under different working conditions are given in Table 3.

Table 3
Average cooling output (W) and COP for the second prototype

Hot water inlet temperatures (°C)	Cooling water inlet temperatures (°C)					
	28		30		32	
90	792.2	0.319	722.5	0.304	659.3	0.290
85	789.6	0.339	718.5	0.321	653.9	0.301
80	680.1	0.319	615	0.298	548.6	0.275
75	558	0.290	–	–	–	–
70	489.3	0.289	–	–	–	–

5. Conclusions

A compact adsorption room air conditioner has been designed, and two prototypes have been built and test experiments also have been conducted. The design cooling capacity is 1 kW, the COP is 0.3–0.5 and the dimensions are 300 mm (depth) × 500 mm (width) × 950 mm (height). Experimental results on the first prototype have shown that a cooling capacity of 687 W and COP of 0.307 can be obtained under typical air conditioning conditions. For the modified prototype, a cooling capacity of 718.5 W and a COP of 0.321 can be reached under the same working conditions. The main conclusions are as follows:

(1) The compact structure and the unique design of evaporator makes the air conditioner suitable to be used in room or other small places.
(2) The novel structure of the adsorption/desorption working chambers (no vacuum valves are needed between the adsorber and the condenser or evaporator) makes the adsorption refrigeration system more reliable.
(3) Operating temperatures ($T_{\mathrm{hw,i}}, T_{\mathrm{cw,i}}$) have strong effects on the cooling output and COP. Basically, increasing $T_{\mathrm{hw,i}}$ and decreasing $T_{\mathrm{cw,i}}$ are beneficial to improve the cooling output and COP, but the COP will decrease when $T_{\mathrm{hw,i}}$ exceeds one certain value.

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