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Study of the performance of activated carbon–methanol adsorption systems concerning heat and mass transfer

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Abstract

Three types of adsorbers and two types of activated carbon–methanol adsorption systems are studied, and the structure of adsorbers, performance of adsorbents, performance of different adsorbers and different systems are compared. Results show that the heat transfer coefficient of solidified bed are much higher than that of granular bed, the design of gas flow channels in adsorbers is very important to the performance of mass transfer and the performance of the whole system. Performance of the adsorber with good design of gas flow channels is much better than that of other two types of adsorbers.

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1. Introduction

Solid–gas sorption heat powered cycles appear to be an attractive alternative for cooling or air conditioning applications due to its environmental benign and can be powered by waste heat and solar energy [1]. Adsorption can be classified as physical adsorption due to a physical process caused by Van der Waals forces, or chemical adsorption in which a chemical process has been involved.

Adsorbents having special affinity with polar substances like water are termed ‘hydrophilic’. These include silica gel, zeolites and porous or active alumina. Non-polar adsorbents, termed

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'hydrophobic', have more affinity for oils and gases than that for water. These substances include activated carbon, polymer adsorbent and silicate. Activated carbon is made by pyrolyzing and carbonising source materials, such as coal, lignite, wood, nutshells and synthetic polymers, at high temperatures (700–800 °C). Activated carbon is available in many forms including powders, micro-porous, granular, molecular sieves and carbon fibres [2].

There are two types of adsorbates used with activated carbon, ammonia and methanol. Many investigations focus on the activated carbon–ammonia system during the current decades [3]. Using a novel carbon molding technique and incorporating a thermal wave regeneration concept, used in the drying of gas streams, a small unit using 0.51 kg of charcoal, developed by Jones [4] at the California Institute of Technology, produced 293 W of cooling with an adsorbent heating and cooling cycle of 6 min with ammonia as adsorbate. A laboratory prototype of an adsorption cooling machine has been designed to demonstrate the effectiveness of the monolithic carbon–ammonia pair by Critoph, and the maximum specific cooling power over the whole cycle and the COP are 60 W/kg and 0.12 respectively [5]. A solar and gas solid sorption machine that uses the active carbon fiber Busofit as a sorbent bed and ammonia as a working fluid was designed and studied by Vasiliev et al. [6]. This adsorption machine has a very short (12 min) non-intermittent cycle and a high solar COP near 0.3 with 1.2 m² solar collection surface and solar collector efficiency being near 0.7. The researches on activated carbon–methanol working pair mainly focus on adsorption systems powered by solar energy. Critoph and Vogel [7] and Meunier [8] studied the performance of activated carbon–methanol, zeolite–water and other working pairs, and the results show that activated carbon–methanol is an ideal working pair for solar energy because of its high COP and low generation temperature. A type of adsorption ice maker with solar energy collector of 6 m² and activated carbon (AC-35) of 130 kg designed by Pons and Grenier could produce 5.3–5.6 kg ice/m² under the radiant intensity of 19–22 MJ [9]. The adsorption system designed by Antonio Pralon is also powered by solar energy and uses activated carbon–methanol as working pair, the optimal COP of a transparent insulation material (TIM) cover system is 0.155 between March and December [10]. Shanghai Jiao Tong University had got lot of achievements on the activated carbon–methanol systems [11–14]. Comparing with activated carbon–ammonia system, activated carbon–methanol system is a vacuum system and that is safer than high-pressure system though not so reliable if a leak exists. Activated carbon–methanol system is powered by low grade heat (70–120 °C). The methanol also has the advantages of high latent heat of evaporation, low freezing point and no corrosion to copper and steel at the working temperature below 120 °C.

Three types of adsorbers using activated carbon–methanol as working pair are discussed in this paper, in which two types of beds are filled with compressively solidified activated carbon and another one is filled with granular activated carbon.

2. Adsorption systems

2.1. Structure of adsorbers

The cross section structure of three types of adsorbers is shown in Fig. 1. The size of cylindrical adsorber1 is $\phi 325 \times 1400$ mm, while adsorber2 and adsorber3 are rectangular with the size as

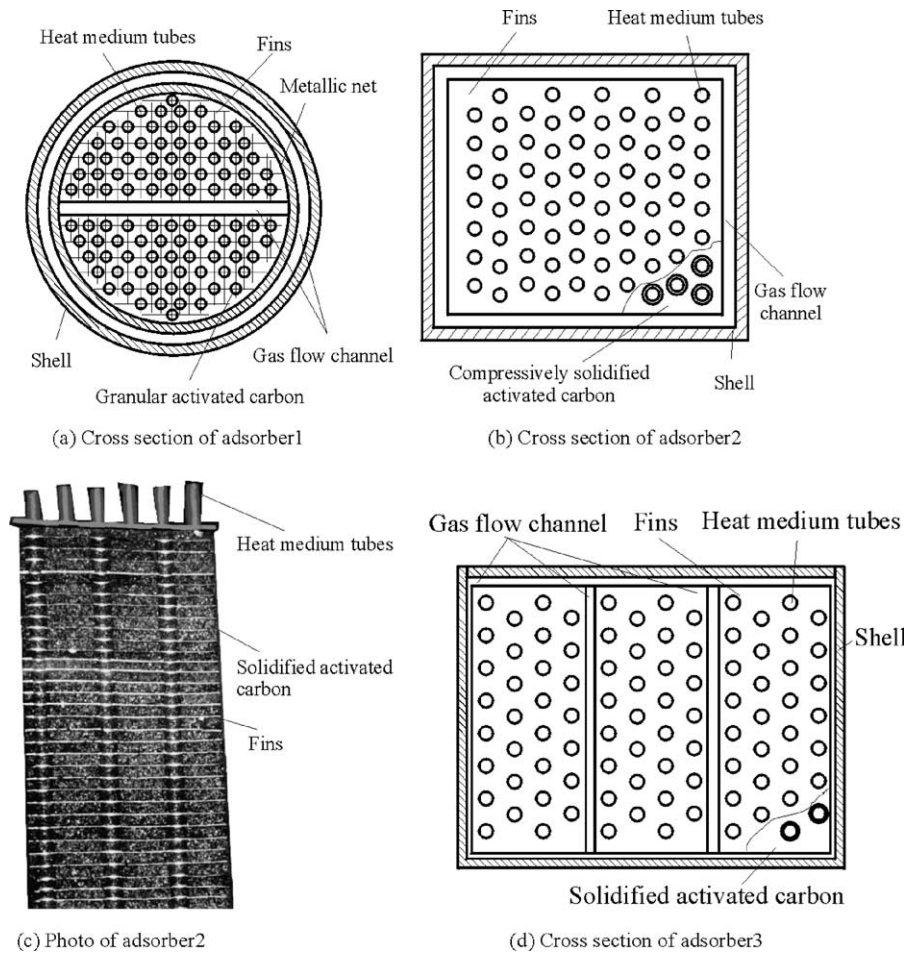


Fig. 1. Cross section structure of adsorbers.

286 × 210 × 2100 mm, and 387 × 422 × 1539 mm respectively. The parameters about three types of adsorbers are shown in Table 1. The heat capacity ratio between adsorbent and adsorber metal are 0.675, 0.813, 0.84 for adsorber1, adsorber2 and adsorber3 respectively.

Granular activated carbon is used in adsorber1, while solidified activated carbon is used in adsorber2 and adsorber3. As is shown in Fig. 1, the mass transfer channels of adsorber3 are more reasonably arranged than that of adsorber2. Water is used as the thermal fluid for cooling and heating of the three adsorbers.

2.2. Performance of adsorbents

The adsorbent in adsorber2 and that in adsorber3 is made by the same method (they are all made by the mixture of the granular activated carbon which is 14–28 mesh and pitch binder), thus

Table 1
Parameters of adsorbers

Adsorber	Item	Material	Mass (kg)	Heat capacity (kJ/°C)
Adsorber1	Thermal fluid tubes	Copper	22.5	8.686
	Fins	Aluminum	5.4	4.907
	Adsorbent	Activated carbon made by the shell of coconut	26	25.6
	Thermal fluid	Water (two-flow circuit)	10	41.8
	Metal of adsorber	Stainless steel	79.1	37.90
Adsorber2	Thermal fluid tubes	Steel	37.6	14.162
	Fins	Steel	9.1	4.205
	Adsorbent	Solidified activated carbon	41	38.13
	Thermal fluid	Water (two-flow circuit)	10.26	42.89
	Metal of adsorber	Carbon steel	111	46.9
Adsorber3	Heat medium tubes	Steel	81.52	30.733
	Fins	Steel	5.71	2.152
	Adsorbent	Solidified activated carbon	60	55.8
	Thermal fluid	Water (four-flow circuit)	14.8	62.08
	Metal of adsorber	Carbon steel	158.51	66.384

their characters are same other than different section parameters. The compressed solidified activated carbon used in adsorber2 has a size of 210 mm × 280 mm × 12 mm, the diameter of holes on it is 19 mm, while the compressed solidified activated carbon used in adsorber3 has a size of

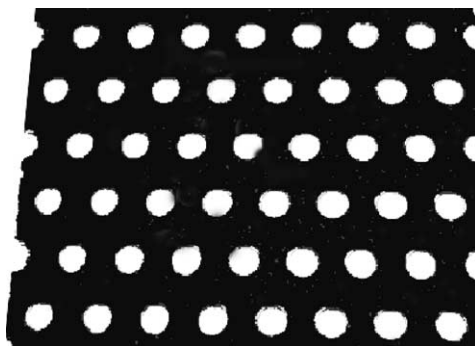


Fig. 2. Structure of solidified activated carbon.

Table 2
Parameters of granular and solidified activated carbon

Parameters	Granular activated carbon bed	Solidified activated carbon bed
Density of adsorbent, kg/m ³	360	600
Heat conductivity of adsorbent, W/(m °C)	0.017	0.27–0.34
Limiting adsorption capacity x_0 , kg/kg	0.284	0.367

116 mm × 272 mm × 10 mm, and the diameter of holes on it is 17 mm. The cross section structure of solidified activated carbon used in adsorber2 is shown in Fig. 2. The parameters of granular and solidified adsorbent are shown in Table 2.

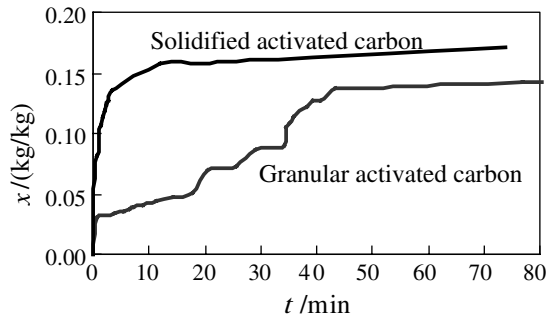


Fig. 3. Adsorption performance of adsorbents.

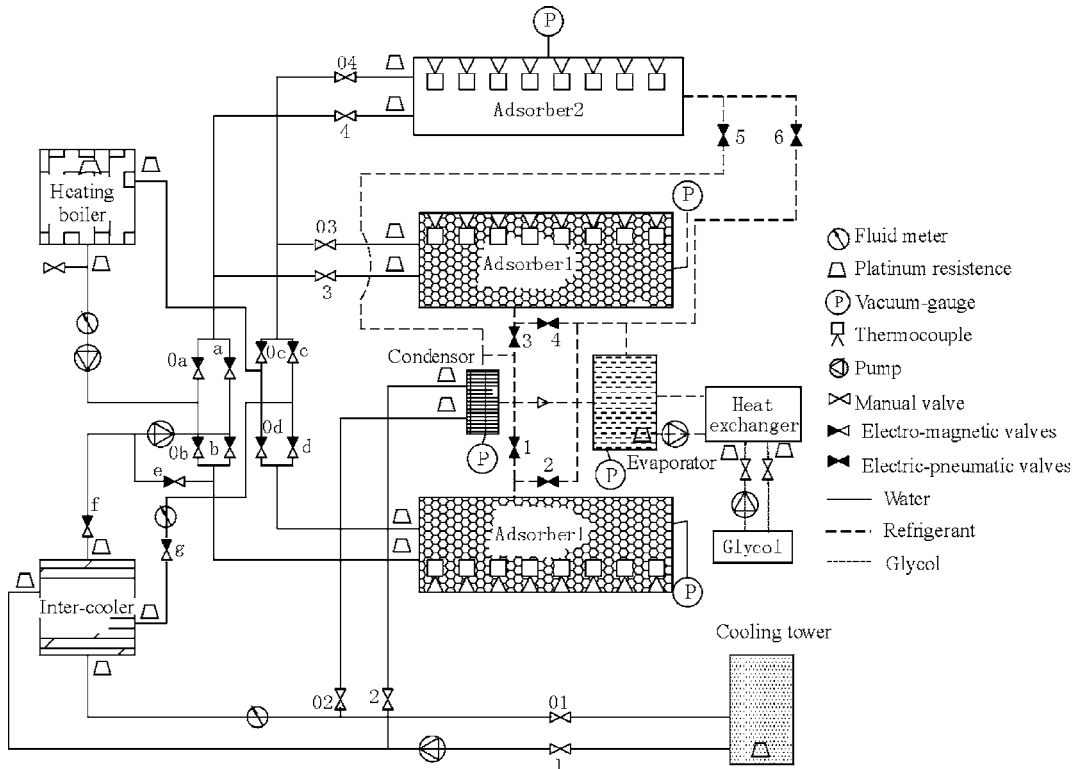


Fig. 4. Schematics of adsorption system for adsorber1 and adsorber2 (system1).

The adsorption performance of granular activated carbon and solidified activated carbon are shown in Fig. 3. It shows that the adsorption performance of solidified activated carbon is much better than that of granular activated carbon.

2.3. Adsorption systems

Adsorption system of adsorber1 and adsorber2 is named system1, shown in Fig. 4. System1 consists of three adsorbers (two beds of adsorber1 and one bed of adsorber2), one condenser, and one evaporator. An electric heating boiler is installed to provide hot water for desorption (controlled below 120 °C). One inter-cooler is used for heat rejection from adsorption bed. Glycol is used as the cooling medium to take the cooling effect outside from the evaporator.

For the adsorption system of adsorber3 that is named system2 (shown in Fig. 5), the cooling water that cools the condenser and adsorber is directly from the city water other than from the heat exchanger, and the cooling effect will be improved. The heat source is diesel engine and the heating boiler would not be used anymore. A hot water storage vessel is used at the exit of gas–water heat exchanger and it serves as a waste heat recovery boiler. The chilled methanol is pumped into the flake ice maker to make ice directly. The photo of flake ice maker and prototype of system2 is shown in Fig. 6. The primary component of flake ice maker shown in Fig. 6 is a stainless steel evaporator disc. The evaporator has a hollow circuitry and is approximately 380 mm in diameter and 13 mm in thickness. Refrigerant flows through passages inside the evaporator

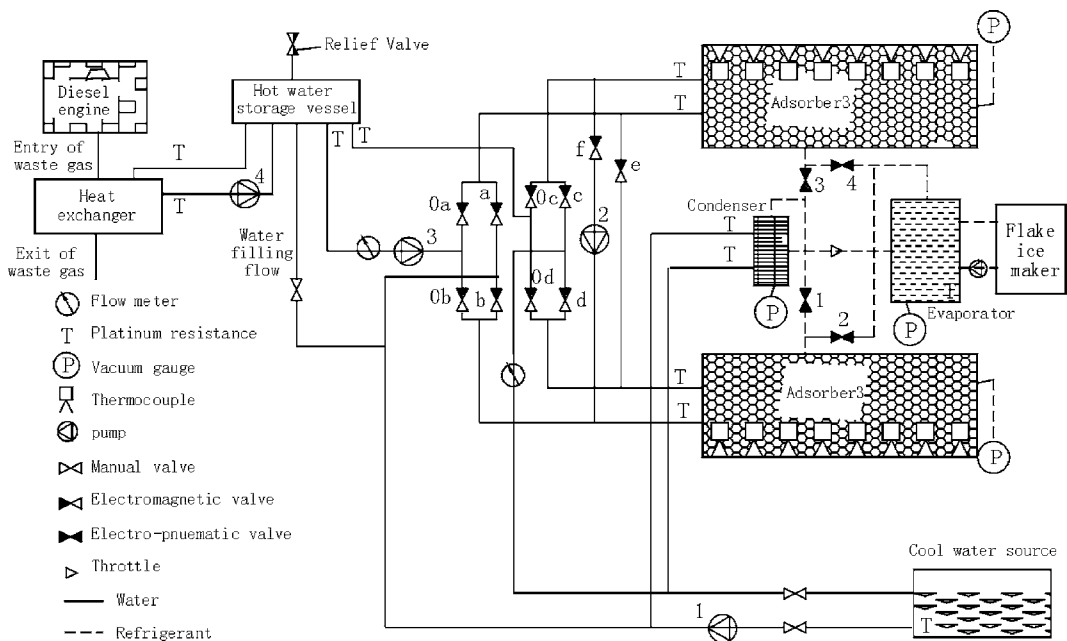


Fig. 5. Schematics of adsorption system for adsorber3 (system2).

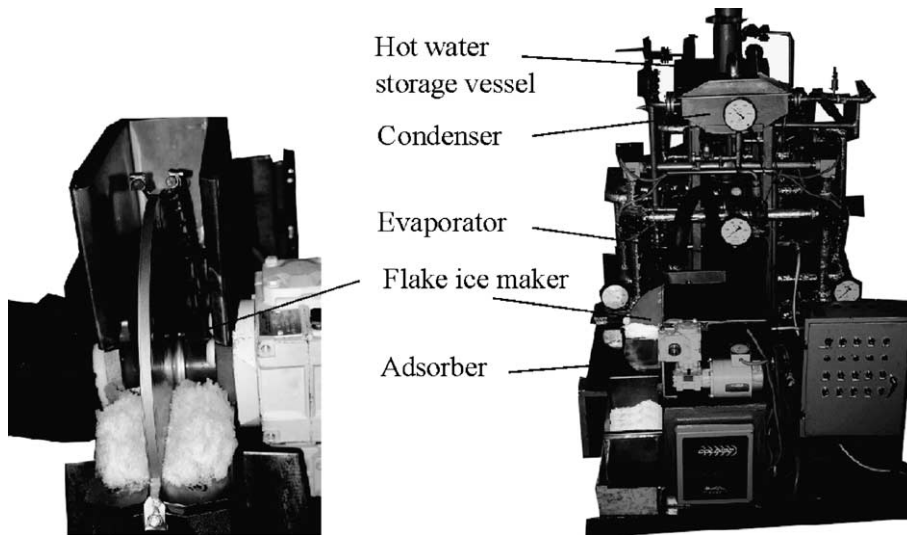


Fig. 6. Prototype for system2 and flake ice maker.

disc removing heat from the freezing surface of the disc. Water is injected on both sides of the disc where it is frozen into a thin layer of ice, the ice is then cut down from the disc surface.

3. Performance of adsorbers

System1 and system2 are used to perform experiments in order to compare performance of three types of adsorbers. Table 3 is the results of the experiments without heat and mass recovery, Table 4 is the results of the experiments on system1 (using adsorber1) with heat and mass recovery, and Table 5 is the results of the experiments with heat and mass recovery on system2.

Table 3
Arrangements and results of experiments

Adsorber	Average temperature of glycol/ice (°C)	Heating temperature (°C)	Cycle time (min)	Desorption and adsorption time (min)	Heat transfer coefficient (W/(m ² °C))	Cooling power (kW)	Average heating power (kW)	COP	SCP (W/kg)
Adsorber1	-7 (glycol)	110			25.4	0.53	12.59	0.042	10.2
Adsorber2			30	15	99.6	0.42	19.49	0.022	10.2
Adsorber3	-4 (ice)	62–100			86.3	1.43	22.75	0.063	11.9
Adsorber1	-7 (glycol)	110			19.1	0.55	9.22	0.059	10.6
Adsorber2			40	20	82.2	0.43	14.78	0.029	10.5
Adsorber3	-5.5 (ice)	67–114			121.5	1.46	22.23	0.065	12.2
Adsorber1	-7 (glycol)	110			20.1	0.57	9.98	0.057	11.0
Adsorber2			50	25	92.4	0.48	15.73	0.031	11.7
Adsorber3	-5.5 (ice)	65–118			81.2	1.58	21.34	0.074	13.2

Table 4
Arrangements and results of experiments on adsorber1

Experiments	Temperature of glycol (°C)	Heating temperature (°C)	Cycle time (min)	Desorption and adsorption time (min)	Recovery time of heat and mass (min)	Cooling power (kW)	Average heating power (kW)	COP	SCP (W/kg)
1	-7	110	36	16	2	0.59	8.76	0.067	11.4
2	-7	110	40	18	2	0.61	7.68	0.080	11.8
3	-7	110	44	20	2	0.63	7.10	0.089	12.1
4	-7	110	48	22	2	0.67	7.00	0.096	12.9
5	-7	110	52	24	2	0.68	6.51	0.104	13.1

Table 5
Arrangements and results of experiments on adsorber3

No.	Heating temp. (°C)	Cycle time (min)	Desorption and adsorption time (min)	Mass recovery time (min)	Heat recovery time (min)	Average evaporation temperature (°C)	Average ice temperature (°C)	Ice produced (kg/h)	Cooling power (kW)	Average heating power (kW)	COP	SCP (W/kg)
1	87–100	36	15	1	2	-5.41	-2.5	12	1.51	15.21	0.088	12.6
2	80–108	46	20	1	2	-9.47	-5.61	13.5	1.72	17.62	0.097	14.3
3	77–107	56	25	1	2	-10.23	-6.61	15	1.92	16.03	0.120	16.0
4	79–116	66	30	1	2	-10.31	-6.63	15.3	1.96	15.63	0.125	16.3
5	78–111	76	35	1	2	-10.97	-7.5	15.4	1.99	17.23	0.115	16.6

3.1. Computation of parameters

Five parameters, heat transfer coefficient, cooling power, average heating power, COP and SCP, are computed from the data of experiments. Heat transfer coefficient (α , W/(m² °C)) in Table 3 is computed by the equation

$$\alpha = \frac{Q \times 1000}{F \Delta t_m} \quad (1)$$

where Q (kW) is heating power, F (m²) is heat transfer area of adsorber, and Δt_m (°C) is average logarithmic temperature difference. Heating power is computed by the formula

$$Q = mc \Delta t \quad (2)$$

where m is the mass flow of water in pipes (kg/s), c is specific heat capacity of water (kJ/(kg °C)), and Δt (°C) is the difference of outlet and inlet temperature which is measured by the platinum resistances for heating boiler and for hot water storage vessel respectively in system1 and system2. Heat transfer area is 24, 17, and 20 m² respectively for adsorber1, adsorber2 and adsorber3. Average logarithmic temperature difference Δt_m (°C) is calculated by

$$\Delta t_m = \psi \frac{\Delta t_{\max} - \Delta t_{\min}}{\ln \frac{\Delta t_{\max}}{\Delta t_{\min}}} \quad (3)$$

where Δt_{\max} (°C) and Δt_{\min} (°C) are respectively maximum temperature difference and minimum temperature difference between the inlet or outlet temperatures and the adsorption bed. ψ is correction factor. Measurement errors of platinum resistances and thermocouples are all 0.15 °C. Error of heat transfer coefficient is computed by the equation

$$d\alpha = \frac{dQ}{F \Delta t_m} - \frac{Q d\Delta t_m}{F \Delta t_m^2} \quad (4)$$

The maximum relative errors for heat transfer coefficients in Table 3 are 8.79%, 9.25%, 7.93% respectively for adsorber1, adsorber2 and adsorber3.

Cooling power of system1 is computed by the formula

$$Q_1 = m_1 c_1 \Delta t_1 \quad (5)$$

where Q_1 (kW) is cooling power; m_1 (kg/s) is the mass flow of glycol; c_1 (kJ/(kg °C)) is specific heat capacity of glycol and Δt_1 (°C) is the difference of inlet and outlet temperature of glycol vessel.

Cooling power of system2 is computed by the ice production, ice temperature and water temperature.

$$Q_1 = m_2 c(t_2 - 0) + m_2 q_z + m_2 c_2(0 - t_3) \quad (6)$$

where m_2 is ice productivity (kg/s); t_2 (°C) is temperature of water; q_z (kJ/kg) is latent heat of icing; t_3 (°C) is ice temperature and c_2 (kJ/(kg °C)) is specific heat capacity of ice.

COP is computed as follows:

$$\text{COP} = \frac{Q_1}{Q} \quad (7)$$

SCP is

$$\text{SCP} = \frac{Q_1}{m_3} \quad (8)$$

where m_3 is the mass of adsorbent in adsorbers.

In the data of the tables (Tables 3–5), maximum relative errors of heating power are respectively 4.92%, 4.53% and 3.94% for adsorber1, adsorber2 and adsorber3. Maximum relative errors of COP are respectively 8.24%, 7.82%, and 6.54%, and maximum relative errors of SCP (as well as that of cooling power) are respectively 5.82%, 5.32% and 3.9% for adsorber1, adsorber2 and adsorber3.

3.2. Heat transfer performance

The average temperatures of each adsorber at a cycle time of 30 min are shown in Fig. 7. Fig. 7 shows that the temperature ascending and descending process of adsorber1 is similar to that of adsorber2, but the temperature ascending and descending process of adsorber3 is much different from other two adsorbers. The temperature of adsorber1 and adsorber2 are all over 100 °C at the time of desorption, but the maximum value of temperature of adsorber3 at the time of desorption

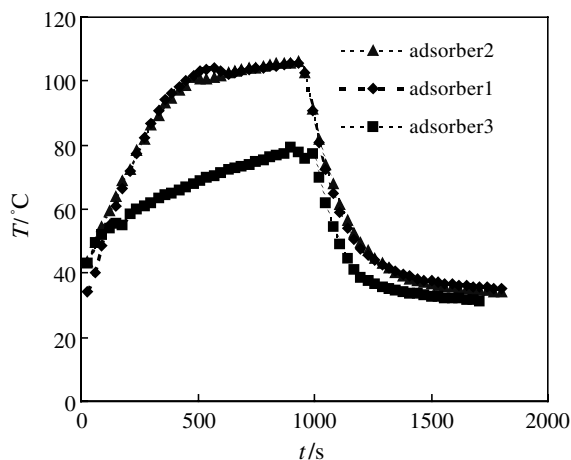


Fig. 7. Average temperature of three adsorbers.

is just over 80 °C. It is caused by the low specific heat capacity of exhausted gas in gas–water heat exchanger. This problem could be solved with two methods, one is to use a bigger hot water storage vessel. The heat capacity of hot water will be greater if the size of hot water storage vessel is greater, and then the temperature fluctuation of thermal medium will be less. Another method is to operate with heat recovery in the experiments.

Heat transfer performance of solidified activated carbon is much better than that of granular activated carbon because the heat transfer coefficients (shown in Table 3) of adsorber2 and adsorber3 are much higher than that of adsorber1.

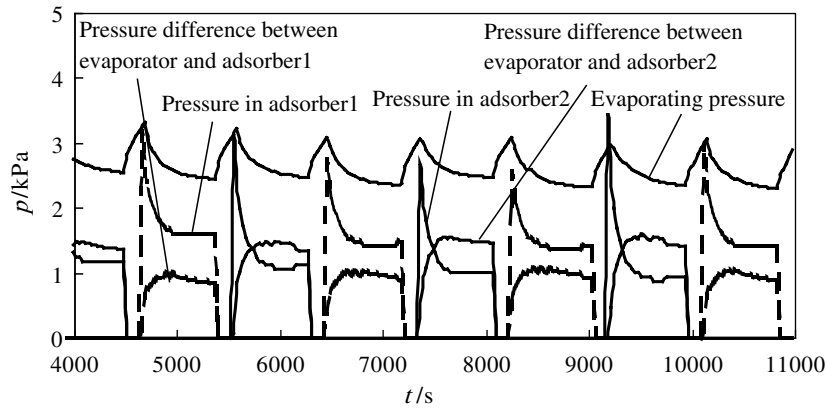
3.3. Mass transfer performance

The mass transfer performance is shown in Fig. 8. The pressure difference between evaporator and adsorber1 is about 1 kPa at the time of adsorption, the maximum difference of pressure between evaporator and adsorber2 is 1.6 kPa, and the maximum pressure difference between evaporator and adsorber3 is only about 0.6 kPa. Thus the mass transfer performance of adsorber3 is much better than other two adsorbers because of the reasonable distribution of gas flow channels. On the contrary, the mass transfer performance in adsorber2 is much worse than other two adsorbers because of less and narrow gas flow channels. COP and SCP of adsorber3 are all higher than that of other two adsorbers (shown in Table 3) because of better performance of mass transfer.

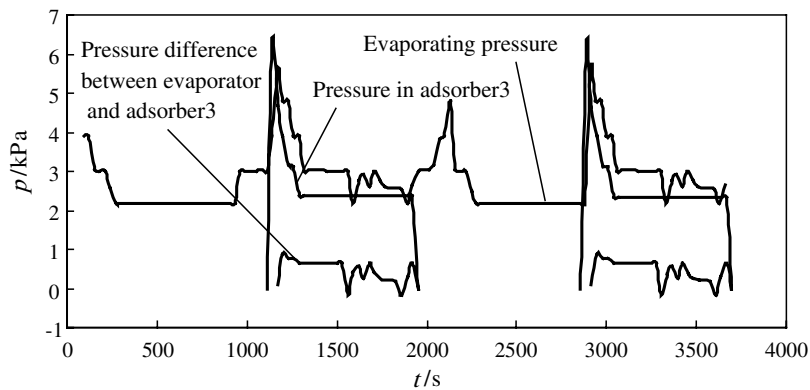
3.4. Experiments with heat and mass recovery

Experiments are performed on adsorber1 (Fig. 4) and adsorber3 (Fig. 5) with heat and mass recovery. The arrangements and results are shown in Tables 4 and 5.

The heat and mass recovery processes for two adsorbers are a little different because of different volume of two adsorbers. In the experiments on the adsorber1, the heat and mass recovery process



(a) Pressure analysis in system1



(b) Pressure analysis in system2

Fig. 8. Pressure analysis at the time of adsorption.

last for 0.5 min and then the valves for mass recovery are shut off, and heat recovery continues to last for another 1.5 min. In the experiments on adsorber3, the mass recovery process last for 1 min, and then the valves for mass recovery are shut off, and heat recovery process begins and last for 2 min. Comparing Table 5 with Table 3, the heating temperature of adsorber3 is enhanced a lot by the heat recovery. The longest cycle time for adsorber1 we chose is 52 min because the ascending rate of cooling power and descending rate of heating power are all small when the cycle time is over 48 min (shown in Table 5). COP and SCP of adsorber3 are respectively about 0.125 and 16 W/kg when the cycle time is 56 min, and the COP and SCP of adsorber1 are respectively about 0.104 and 13.1 W/kg when the cycle time is 52 min. Performance of adsorber3 is much better than that of adsorber1.

4. Conclusions

Three adsorbers with different structures and different adsorbents are studied by the performance tests. This research has shown:

- (1) Design of gas flow channels is very important to the performance of adsorbers, especially to compressively solidified beds. The mass transfer performance and the working performance of adsorber3 are all higher than that of other two adsorbers because of the reasonable design of gas-flow channels.
- (2) Heat transfer performance of solidified beds is much higher than that of granular beds. The heat transfer coefficient of solidified beds is about 80–120 W/(m² °C), and the heat transfer coefficient of granular beds is only about 19–26 W/(m² °C). The heating efficiency in the system driven by exhausted gas (simulated by the oil burner) is lower than that in the system driven by heating boiler because the heat exchange efficiency of gas–water heat exchanger is low.
- (3) Experiments with heat and mass recovery on adsorber1 and adsorber3 show that the performance of adsorber3 is much better than that of adsorber1. COP and SCP of adsorber3 are respectively about 0.125 and 16 W/kg when the cycle time is 56 min. COP and SCP of adsorber1 are respectively about 0.104 and 13.1 W/kg when the cycle time is 52 min.

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