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Experimental results on operating parameters influence for an adsorption refrigerator ☆

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Abstract

A continuous heat recovery adsorption refrigerator using activated carbon-methanol has been developed. In this system, the heat source to drive the adsorption system can be controlled at a temperature from 60 °C to 110 °C, and the evaporating temperature can also be controlled at any requested value from 0 °C to 15 °C. To realize the operation performance of the system, many sensors of temperature, pressure and flow rate are installed in the adsorbers, the condenser and the evaporator. A lot of experiments have been completed in different operation conditions. Thus, by means of the experimental data, influences of the operating parameters, such as heat source temperature, evaporating temperature, cooling water temperature, cycle time and flow rate of throttling valve and so on, on *p-t-x* diagram of the cycle, specific cooling power (SCP) and coefficient of performance (COP) have been asserted. And causes of the influence are also analyzed. A series of conclusions are obtained.

Keywords: Adsorption refrigerator; Operating parameters; System performances; Experimental research; Coefficient of performance

1. Introduction

With replacement of CFCs actuating media, some new types of refrigerators are developed gradually, especially adsorption refrigerators, in which heat recovery adsorption refrigerator is an advanced one developed in recent years. It has many advantages such as simple system components, easy realization of cycles. In research on adsorption refrigeration system, there are

(1) an adsorption refrigerator in which direct contact condensation and evaporation on sprayed water were used, a COP close to 0.58 is reached under the conditions of inlet temperature of hot/cooling/chilled water 70/29/14 °C [1],
(2) an adsorption chiller driven by low-grade waste-heat with a maximum COP reaching 0.44 under the condition of inlet temperature of hot/cooling/chilled water 50/20/16 °C [2],
(3) a two-adsorber solid adsorption heat pump with a COP of 0.67 using zeolite–water pair [3],
(4) an adsorption heat pump with a COP of 0.6 using activated carbon fiber–methanol pair [4],
(5) an adsorption refrigerator with a COP of 0.4 using activated carbon–methanol pair [5].

In a continuous heat recovery adsorption refrigerator, the parameters affecting system performances mainly include desorption temperature, adsorption temperature, condensing temperature, evaporating temperature, cycle time, heat recovery time, etc. Desorption temperature is influenced by heat source temperature, and adsorption temperature and condensing temperature are related to cooling water temperature. Therefore, main factors influencing the system operation include heat source temperature, cooling water temperature, evaporating temperature, cycle time and heat recovery time, etc. In addition, in the continuous heat recovery system, the throttling valve also plays an important role. In the research, Saha [6] analyzed the influences of the operation conditions on refrigerating capacity in theory for silica gel–water adsorption refrigeration system. The operation conditions include hot/cooling water temperature, flow rate of water and cycle time. Cacciola [7], Zheng [8], Teng [9] also analyzed the influences of desorption temperature,

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Nomenclature

c_p	specific heat of chilled water	$kJ \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$
$\dot{m}$	flow rate of chilled water	$kg \cdot s^{-1}$
M	mass of adsorbent in one adsorber	kg
Q_{ref}	refrigerating capacity in one cycle	kJ
t	time	s
t_{cycle}	cycle time of the system operations	s
T_{cool}	cooling water temperature	°C
T_e	evaporating temperature	°C
$T_{heat,s}$	heat source temperature	°C
t_{reg}	heat recovery time	s
$T_{w,in}$	inlet temperature of chilled water	°C
$T_{w,out}$	outlet temperature of chilled water	°C
Δt	interval of data acquisition	s
ΔW	recorded electric energy in one cycle	kJ

adsorption temperature, evaporating temperature and condensing temperature on the refrigerating capacity and COP in theory. In recent years, we have developed a continuous heat recovery adsorption refrigerator using activated carbon-methanol [10]. The research of the dynamic simulation has been completed [11]. A lot of experiments have been also completed for the system. In this paper, Influences of the system operating parameters, such as heat source temperature, evaporating temperature, cooling water temperature, cycle time and stroke of throttling valve, on *p*-*t*-*x* diagram of the system cycle and specific cooling power (SCP) and coefficient of performance (COP) are discussed through analyzing experimental data. And the causes of influence are also analyzed. A series of conclusions are obtained.

2. The continuous heat recovery adsorption refrigerator

2.1. Description of the system

The schematic of the developed continuous heat recovery adsorption refrigerator using activated carbon-methanol is shown in Fig. 1. The properties of the activated carbon are shown in Table 1. When the system is driven by 100 °C hot water, a COP of 0.4 and a SCP of $150 W \cdot kg^{-2}$ can be obtained.

The system consists of two parts. The first part includes two adsorbers, a heater and a cooler. One adsorber discharges refrigerant vapor to the condenser under high temperature and high pressure. The other adsorber adsorbs refrigerant vapor from the evaporator under low temperature and low pressure. In this way, refrigerant inside the evaporator keeps evaporating which produces refrigerating effect. If the two adsorbers desorbe and adsorbe alternatively, the continuous refrigerating capacity can be obtained. The second part includes a condenser, a throttling valve and an evaporator. After the refrigerant vapor under high temperature and high pressure is cooled in the condenser. Then it goes through the throttling valve and change into liquid vapor mixture under low temperature and low pressure. The liquid enters the evaporator for evaporating and refrigerating. The evaporated refrigerant vapor will be adsorbed again by the adsorber.

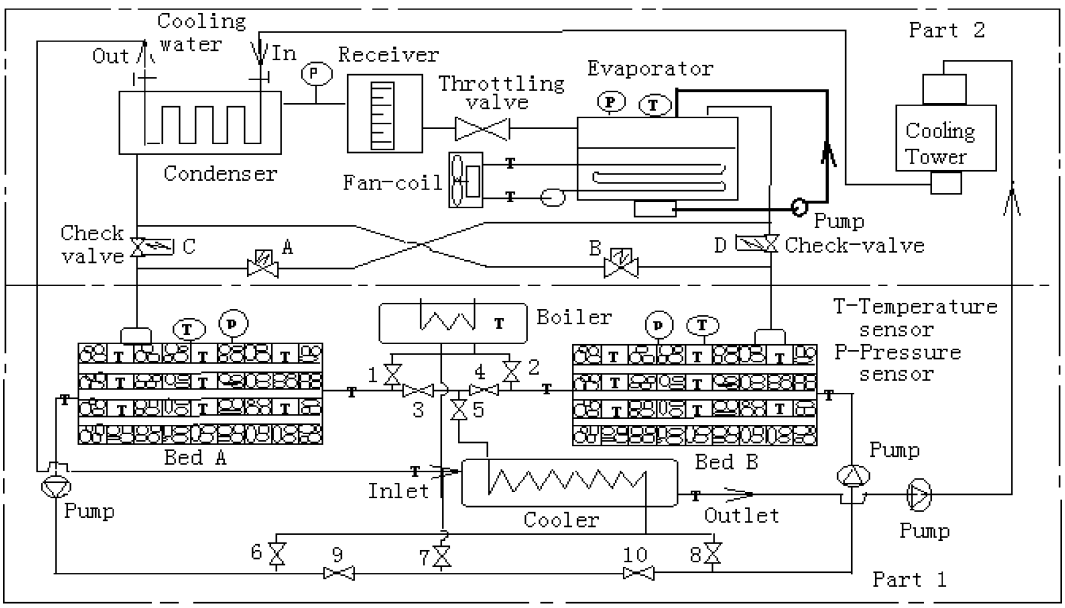

Fig. 1. Schematic of the continuous heat recovery adsorption refrigerator.

Table 1
Properties of the activated carbon

Sample	Specific surface area ($m^2 \cdot g^{-1}$)	Density ($kg \cdot m^{-3}$)	Size (mesh)	Original material	Manufacturer
ACYK	1200	620	$8 \sim 20$	Coconut shell	Shanghai

Two novel shell and tube type heat exchangers of 1.2 m length and 0.3 m diameter are constructed to be the two adsorbers with 9.5 mm tube diameter, and the distance between the tubes is 25 mm. The adsorbent of 26 kg for each adsorber is filled in the shell, and water or oil is used as the heat transfer medium which goes through the tubes. Eight temperature sensors, which are expressed as '*T*' inside two adsorbers of Fig. 1, are installed at different positions outside the tubes in order to properly measure the adsorbent temperature. Therefore the temperature of the adsorber is the average of this eight temperatures. The heat transfer coefficient of the adsorber is about 90 $W \cdot m^{-2}$ °C, which was obtained from experiments. The heat source is an electric boiler about 100 liters, with the highest heating power of 30 kW, which can provide hot water from 60 °C to 110 °C. The adsorber and the condenser are cooled by water from a cooling tower. The refrigerating capacity is output to two fan-coils by chilled water circulation. The condenser is a plate type heat exchanger, and the evaporator is a spray type one.

An ideal cycle of a continuous heat recovery adsorption refrigeration system is shown in Fig. 2 [3]. The cycle path of an adsorber goes along a-b-c-d in Fig. 2. The heating phase can be divided into two processes: (1) isosteric regeneration process a-b, in which an adsorber, for example adsorber A of Fig. 1, is heated from T_{a1} to T_{g1}, meanwhile, valve C connecting the adsorber with the condenser is closed during this period; (2) isobaric desorption process, in which the adsorber is heated from T_{g1} to T_{g2}, meanwhile, valve C is open to connect the adsorber with the condenser. Similarly the cooling phase is also divided into two processes: (1) isosteric cooling process, in which the adsorber is cooled from T_{g2} to T_{a2}, meanwhile, valve A connecting the adsorber with the evaporator is closed during this process; (2) isobaric adsorption process, in which the adsorber is cooled from T_{a2} to T_{a1}, meanwhile, valve A is open to connect the adsorber with the evaporator. For the system of two adsorbers, there is a heat recovery process. When two adsorbers complete one cycle and start to change their working states, the adsorber (for example, adsorber A in Fig. 1) that has just finished desorbing process will be cooled down so that it will release a lot of heat. Meanwhile, the adsorber (for example, adsorber B in Fig. 1) that has just finished adsorbing process will be heated so that it needs a lot of heat. Therefore, heat discharged by the adsorber (adsorber A) can be used to heat the another adsorber (adsorber B) if they are connected together. The ideal recoverable heat includes both the sensible heat of isosteric cooling process c-d and the sensible heat and adorption heat of isobaric adsorption process d-e_1. But in real operation there is a heat recovery temperature difference between the two adsorbers when the heat recovery process is over.

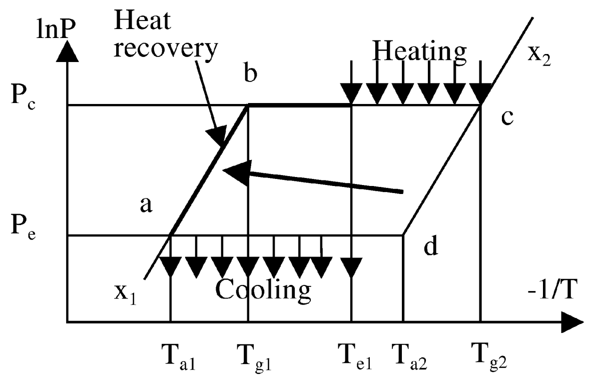

Fig. 2. P-t-x diagram of ideal cycle for two adsorbers.

For the heating and cooling loop of adsorber, there are three states:

(a) adsorber A is heated, adsorber B is cooled when valve 1, 4, 5, 7, 8, 9 are open and valve 2, 3, 6, 9, 10 are closed;
(b) adsorber A and adsorber B are linked for heat recovery when valve 3, 4, 9, 10 are open and valve 1, 2, 5, 6, 7, 8 are closed;
(c) adsorber A is cooled, adsorber B is heated when valve 2, 3, 5, 6, 7, 10 are open and valve 1, 4, 8, 9 are closed.

The theoretically calculated COP is 0.54 under heat source temperature of 100 °C, cooling water temperature of 21 °C, evaporating temperature of 6 °C, heat recovery temperature difference of 5 °C in the end of the heat recovery process. The calculation method and equations are shown in the literature [12]. The second law efficiency from theoretical COP based on three-temperature Carnot COP [13] is 0.1, the second law efficiency from experiment is 0.08. At the working condition above and cycle time of 40 min. Special cooling power is 168 $W \cdot kg^{-1}$ in theoretical calculation.

2.2. Control of the evaporation temperature

The two-adsorber adsorption refrigerator makes use of the shifts of two adsorbers to obtain continuous refrigerating effect. On the one hand, when an adsorber begins the desorption process, its adsorption capacity is the strongest. With the increase of the adsorption time, the adsorption capacity will reduce down gradually. Thus, during the adsorption

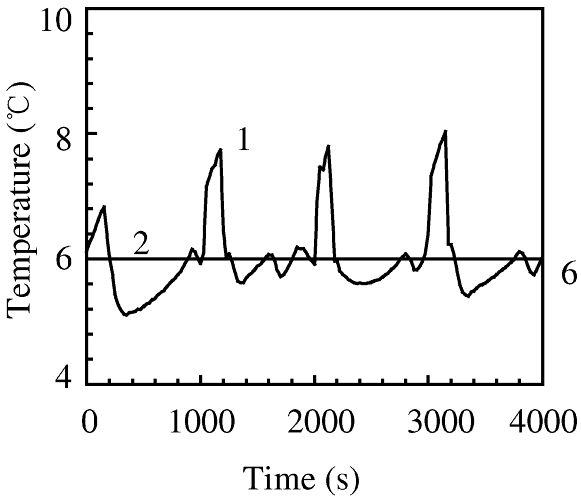

Fig. 3. Evaporating temperature vs. Time for a typical test.

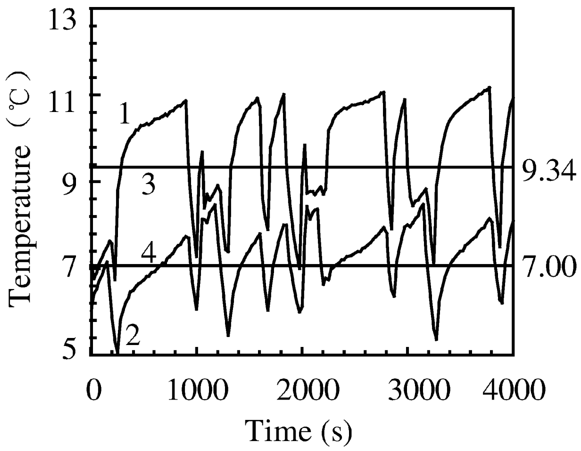

Fig. 4. Chilled water temperature and its averaging, 1—inlet temperature, 3—averaged inlet temperature, 2—outlet temperature, 4—averaged outlet temperature.

process, the refrigerating power varies from time to time. On the other hand, it takes several minutes for the adsorber to complete the isosteric cooling process. During this process, the adsorber does not have adsorption capacity so that there is no refrigerating effect to be produced. Therefore, in order to guarantee a stable evaporating temperature and make the heat input from outside match the refrigerating capacity at any time, the fan speed of the fan-coils is controlled, which is controlled at four states of high, medium, low or off, according to the expected evaporating temperature. By setting of evaporating temperature and also averaging of the recorded value, the proper experimental evaporating temperature is determined.

Fig. 3 shows an example of a test, the set value is 6 °C, average value of the recorded data is also 6 °C.

2.3. Calculation of COP (Coefficient Of Performance) and SCP (Specific Cooling Power)

Two fan-coils each with a maximum heat transfer capacity of 5 kW are used to output the refrigerating effect to the room space. The refrigerating power is evaluated by the flow rate of chilled water multiplied by the temperature difference of the chilled water at the inlet and outlet. A chilled water pump is switched on all the time. The measured temperature difference varies with the fan speed of the fan-coils. The different temperature difference shows the different refrigerating capacity. Therefore, the refrigerating capacity for one cycle is calculated as:

$$Q_{\mathrm{ref}} = \int_0^{t_{\mathrm{cycle}}} \dot{m} \cdot c_{\mathrm{p}} \cdot (T_{\mathrm{w,in}} - T_{\mathrm{w,out}})\,\mathrm{d}t \approx \dot{m} \cdot c_{\mathrm{p}} \cdot \Delta t \cdot \sum_{i=1}^{k} (T_{\mathrm{w,in},i} - T_{\mathrm{w,out},i}) \tag{1}$$

where Q_{ref} is the refrigerating capacity in one cycle (kJ), c_{p} is the specific heat of chilled water (kJ·kg^{-1}, °C), $\dot{m}$ is the flow rate of the chilled water (kg·s^{-1}), $T_{\mathrm{w,in}}$, $T_{\mathrm{w,out}}$ are inlet and outlet temperature of the chilled water (°C), t_{cycle} is the cycle time of the system operation (s), t is time (s), Δt is the interval of data acquisition (s), i is the order of the measured data in one cycle, k is the total numbers of the measured data in one cycle.

The typical curves of chilled water temperature vs. time are shown in Fig. 4. Inlet and outlet temperature averaging of the chilled water can be done with the measured data, thus the mean temperature difference of chilled water can be obtained.

The total heat input of the heat source is calculated according to the electric energy meter, which is recorded manually. This value is higher than real heat input, as there are heat leaks in the system. COP is calculated as

$$COP = Q_{\mathrm{ref}}/\Delta W \tag{2}$$

where ΔW is the recorded electric energy in one cycle (kJ). In Eq. (2), the evaluated Q_{ref} and ΔW are based upon one or two cycles after the system is close to steady operation (steady operation usually needs 2 cycles from our experimental experiences).

According to the system characteristics, Specific cooling power of the system is defined as:

$$SCP = (Q_{\mathrm{ref}}/t_{\mathrm{cycle}})/M \tag{3}$$

in which M is the mass of adsorbent in one adsorber (kg).

2.4. Deviation of the measured data

The measurement device is a digital voltmeter of $6\frac{1}{2}$ digit with 40-channels. The measurement sensors used and the accuracy of the measurement are displayed in Table 2. In the experiment, average difference of inlet and outlet temperature of the chilled water is more than 2 °C. The flow rate of the chilled water is more than 1 m^3·h^{-1}. According to Eq. (1), the deviation of Q_{ref} is in 8%. The measuring deviations of both the electric energy and the

Table 2
Measured quantity, used measurement sensor and their accuracy in the system

Measured quantity	Sensor	Accuracy
Temperature inside the adsorbers	Thermocouple(Cu-CuNi,Type T)	±0.4 °C
Temperature of the chilled water	Pt-100 (4-wire measurement)	±0.06 °C
Temperature of the condenser cooling water	Pt-100 (4-wire measurement)	±0.1 °C
Temperature inside the evaporator	Pt-100 (4-wire measurement)	±0.06 °C
Pressure inside the adsorbers	Film pressure sensor	±8 Pa
Pressure inside the evaporator	Film pressure sensor	±8 Pa
Flowrate of the chilled water	Revolving flowmeter	$\pm 0.02\ m^3 \cdot h^{-1}$

mass of adsorbent are in 1%, which can be ignored, thus, the deviation of *SCP* and *COP* is the same as the deviation of Q_{ref}.

3. Cycle time influence on system operating performances

Cycle time is an important operating parameter of the system. Usually, the shorter the cycle time, the greater the refrigerating power is. But if the cycle time is too short, the adsorbent cannot be heated to a higher temperature or cooled to a lower temperature due to limitation of heat transfer of adsorber; therefore there is no enough desorption and adsorption capacity for the adsorber in one cycle. In addition, the desorption and adsorption capacity of adsorber is related not only to temperature but also to time owing to limitation of mass transfer of adsorber. If the cycle time is too short, there is no enough time for the adsorber to complete desorption and adsorption process. In this way, refrigerating capacity will decrease, which will also influence SCP and COP. Therefore, for making the system operate in a better condition, selection of cycle time is very important. Both the refrigerating power and time needed for adsorption and desorption process shall be taken into consideration, which is related to heat transfer and mass transfer properties of the adsorbers as well as performance of condenser and evaporator.

3.1. Cycle time and p-t-x diagram of system operation

Fig. 5 shows p-t-x diagram of the actual operation with a 30-minutes, 40-minutes and 50-minutes cycle time. Fig. 5 also shows that p-t-x diagrams of the real cycles are quite different from those of the ideal cycles: adsorption process of the system cycle is near to the isothermal adsorption, desorption process of the system cycle is located in the isothermal desorption and the isobaric desorption. This is chiefly due to the limitation of heat transfer of the adsorbers and the limitation of condenser's cooling capacity. In the adsorption process, there is a lot of adsorption heat rejected. If heat transfer of the adsorber is limited, the cooling medium of the adsorber can but take away the adsorption heat, which will result in less change of the adsorber temperature and rising of the adsorber pressure. At the

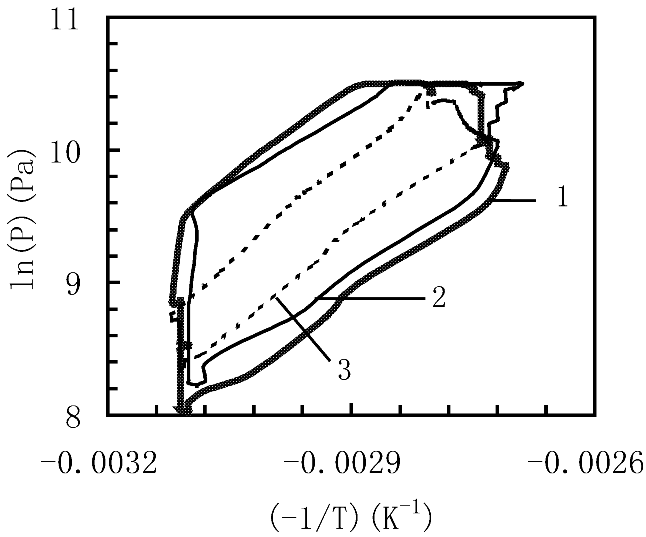

Fig. 5. P-t-x diagram under different cycle times, 1—50 min, 2—40 min, 3—30 min, the other operation parameters are $T_{heat,s} = 100\,°C$, $T_{cool} = 21\,°C$, $t_{reg} = 120$ s.

beginning of desorption process, the desorbed refrigerant vapor cannot be condensed in time because of the limitation of condenser's cooling capacity, which leads to change of the adsorber pressure from low to high. While decreasing of the desorbed refrigerant vapor amount, the condenser's cooling capacity is becoming strong, which leads to change of the adsorber pressure from high to low.

When cycle time is 30 minutes, the adsorber has no enough time to carry out desorption and adsorption process due to the limitation of time. As the cycle time is increased, the desorption and adsorption process of the system cycle will be more complete, the flow rate of refrigerant will be increased. The p-t-x diagram with cycle time of 40 minutes and 50 minutes are more similar to each other than that of 30 minutes. With increasing of cycle time, the adsorber works more close to the steady cycle, finally the desorption and adsorption capacity will reach their maximum. Therefore, p-t-x diagram will not change much for sure when cycle time is greater than 50 minutes.

3.2. Cycle time and COP and SCP of system operation

SCP and COP are related not only to the adsorption capacity of the adsorber in each cycle, but also to the cycle time. Fig. 6 shows the experimental data reflecting relationship between cycle time and SCP and COP: Cycle time with maximum SCP is 40 minutes and in this cycle time COP is 94.9% of its maximum value. Cycle time with maximum COP is 50 minutes, and in this cycle time, SCP is 97.6% of its maximum value.

In order to obtain a maximum COP, for each cycle the adsorber should desorb or adsorb the more refrigerant, in this case it takes more time to complete a cycle, in other words, a longer cycle time is needed. But in a longer cycle time, the smaller specific cooling power will be yielded. This is a contradiction. In the design of an adsorption refrigerator, a compromise between COP and SCP should be considered. The method of solving the contradiction is to improve heat and mass transfer performance of adsorber.

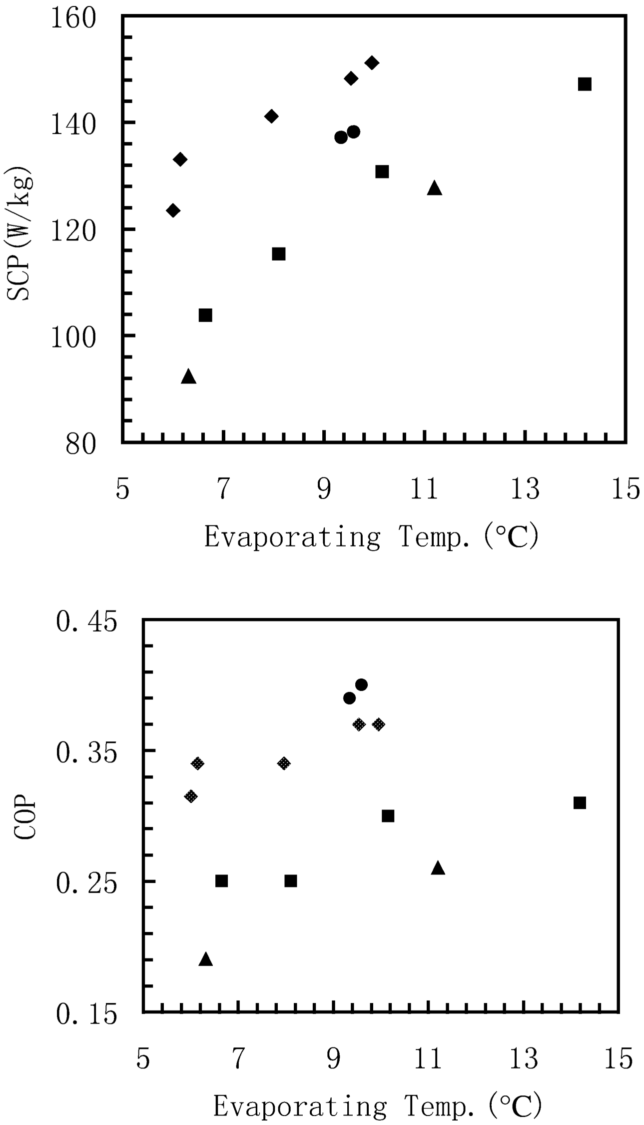

Fig. 6. Cycle time and SCP and COP, ▲—20 min, ■—30 min, ♦—40 min, •—50 min, the other operation parameters are $T_{\text{heat,s}} = 100\,^{\circ}\text{C}$, $T_{\text{cool}} = 21\,^{\circ}\text{C}$, $t_{\text{reg}} = 120$ s.

4. Heat source temperature and system operating performance

Desorption temperature is another important operating parameter. Generally, the higher the heat source temperature, the quicker the temperature-up speed of adsorber is and the higher desorption temperature is. Therefore, there is the larger SCP for a higher heat source temperature. But when the heat source temperature increases gradually, COP start to goes up, then reach a maximum COP, finally goes down.

4.1. Heat source temperature and p-t-x diagram of system operation

From a dynamic viewpoint, increasing of the heat source temperature improves heating speed of the adsorber and also heighten the desorption temperature, therefore, one cycle will yield more desorption capacity. In other words, a higher heat source temperature improves adsorber's capability. The p-t-x diagram of the actual operation is shown in Fig. 7, in which the heat source temperatures of 90 °C, 100 °C and 110 °C are included. Fig. 7 shows that the increasing of heat source temperature reduces the desorption pressure of adsorber and realizes enough desorption process. This effect can be compared with prolonging desorption time to yield more desorption capacity.

By comparing curve 2 in Fig. 5 and curve 1 in Fig. 7, adsorber's performance under 30-minutes cycle time and heat source temperature of 110 °C is close to that under 40-minutes cycle time and heat source temperature of 100 °C. That indicates that the increase of heat source temperature results in the increase of adsorber's performance.

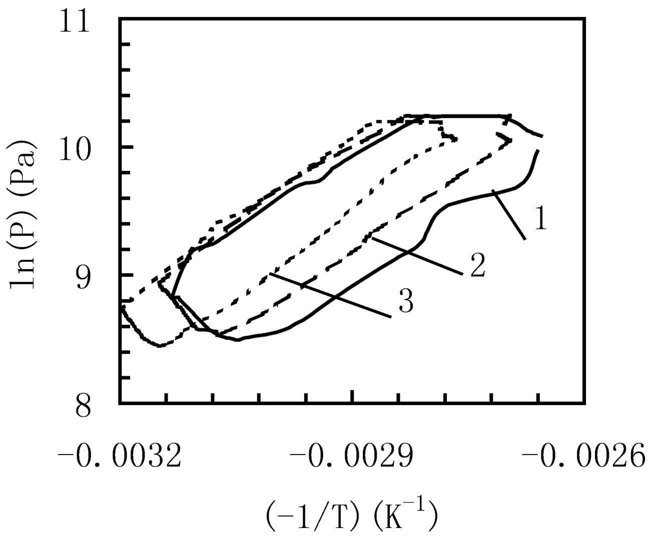

Fig. 7. P-t-x diagram under different heat source temperatures, 1—110 °C, 2—100 °C, 3—90 °C, the other operation parameters are $T_{\text{cool}} = 21\,^{\circ}\text{C}$, $t_{\text{cycle}} = 30$ min, $t_{\text{reg}} = 120$ s.

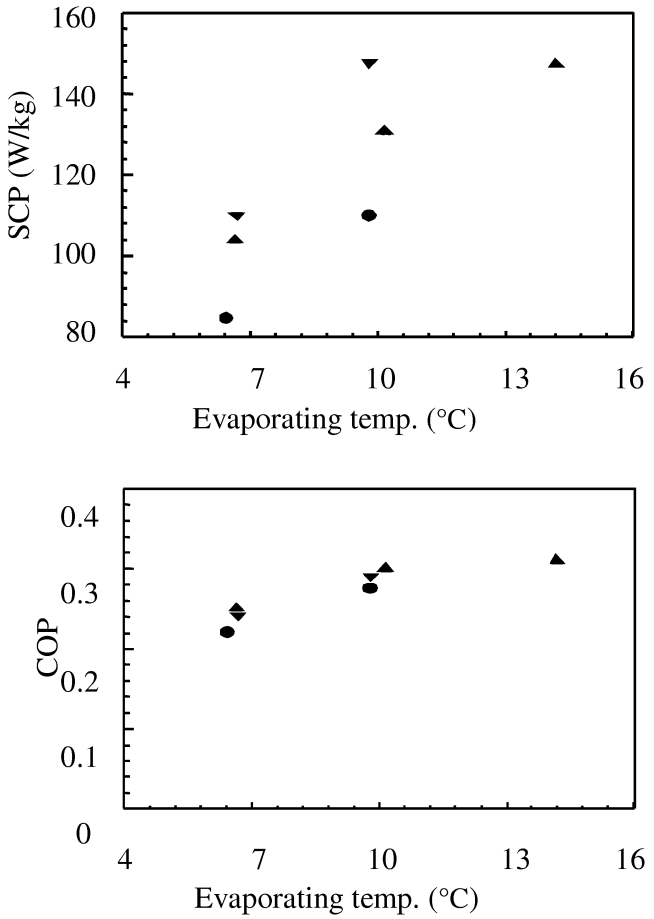

Fig. 8. Heat source temperature and SCP and COP, ▼—110 °C, ▲—100 °C, •—90 °C, the other operation parameters are $T_{\mathrm{cool}} = 21\,^{\circ}\mathrm{C}$, $t_{\mathrm{cycle}} = 30$ min, $t_{\mathrm{reg}} = 120$ s.

4.2. *Heat source temperature and COP and SCP*

The increase of heat source temperature makes adsorber working better in the same cycle time, which will definitely increase SCP. However, the rising of heat source temperature also increases heat output of the heat source. Fig. 8 shows SCP and COP of the system operation under different heat source temperature. Experiment data shows that SCP gradually increases with the rising of the heat source temperature, but for COP there is a maximum value. The heat source temperature with maximum COP is 100 °C.

5. Stroke of throttling valve and system operating performance

In the adsorption refrigerator, the throttling valve controls refrigerant flow from condenser to evaporator. It is one of the main parts keeping the system working continuously. If the stroke of this throttling valve is too wide, condenser and evaporator will have passage to each other and thus influence evaporating pressure; if the stroke is too narrow, the flow of refrigerant will be influenced and thus desorption capacity reduced. Therefore, a proper stroke of throttling valve is demanded. A 2 mm needle valve is adopted here with a controlled stroke range of 10 mm. To know the influence of stroke of throttling valve on system operating performance, the comparing experiments under two groups of working conditions are carried out. The experimental data are shown in Fig. 9 and Fig. 10. Fig. 9 shows a variety of the inlet and outlet temperatures of the condenser cooling water, and Fig. 10 shows a variety of refrigerating power. Hereafter working condition with 2 mm stroke is referred to as working condition 1 and working condition with 5 mm stroke is referred to as working condition 2.

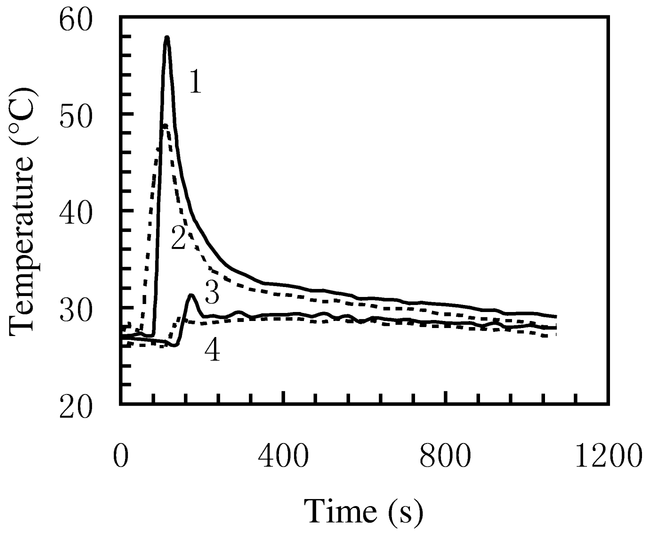

Fig. 9. Comparison of inlet and outlet temperature of condenser cooling water, stroke of the throttling valve: −2 mm, −5 mm, in which 1, 2—outlet temperature of condenser cooling water; 3, 4—inlet temperature of condenser cooling water.

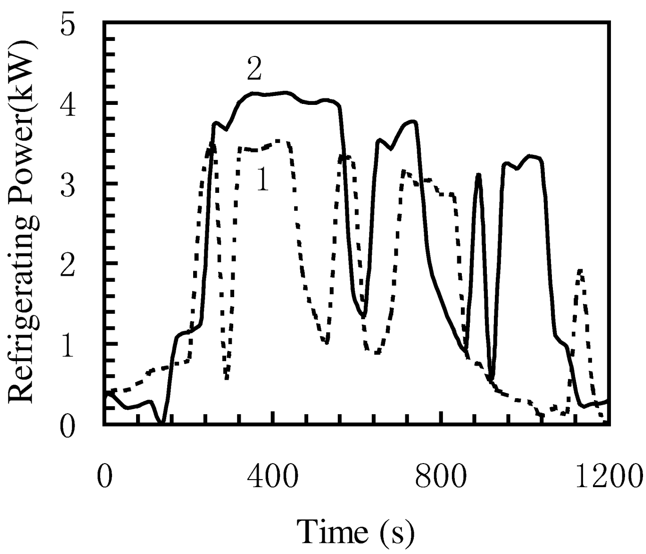

Fig. 10. Refrigerating power vs. time for different strokes of the throttling valve, stroke of the throttling valve: 1—2 mm, 2—5 mm.

Fig. 9 shows the greater condenser's cooling capacity for working condition 2. It indicates that the desorption capacity of working condition 2 is greater. The reason is that the opening of throttling valve vacuumizes the condenser's room, causes the flowing of refrigerant and improves desorption process. In this way, it laid a good foundation for adsorption process in the next cycle. Therefore, in experiment under working condition 2, opening of throttling valve increases refrigerating power of system operation. Fig. 10 shows that refrigerating power under working condition 2 is greater than that under working condition 1.

6. Cooling water temperature and system operating performances

Adsorption temperature is closely related to inlet temperature of adsorber cooling water. Generally, the lower inlet temperature of the cooling water, the quicker adsorber's temperature decreasing speed is and the lower adsorption temperature is, therefore the greater refrigerating power in the same cycle time is. Fig. 11 shows comparison of the *p-t-x* diagram under two different temperatures of cooling water. The curves in Fig. 11 show that increase of cooling water temperature results in increase of adsorption temperature and causes increase of desorption pressure. It is because that cooling water temperature influences not only the adsorption temperature, but also the condensing temperature, therefore, adsorption capacity in adsorption process is influenced, so is the desorption process. Changing of system's adsorption and desorption capacities results in changing of refrigerating power. Fig. 12 shows the comparison of refrigerating power under two different temperatures of cooling water.

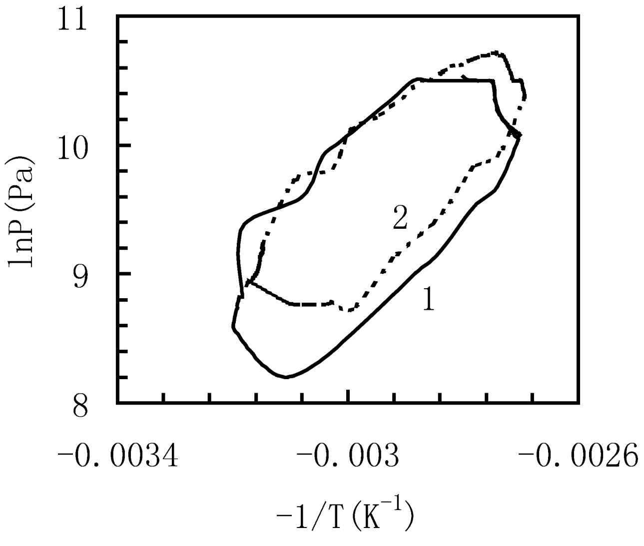

Fig. 11. *P-t-x* diagram under two different cooling water temperatures, 1—21 °C, 2—27 °C, the other operation parameters are $T_{\text{heat,s}} = 100\,°\text{C}$, $t_{\text{cycle}} = 40$ min, $t_{\text{reg}} = 120$ s.

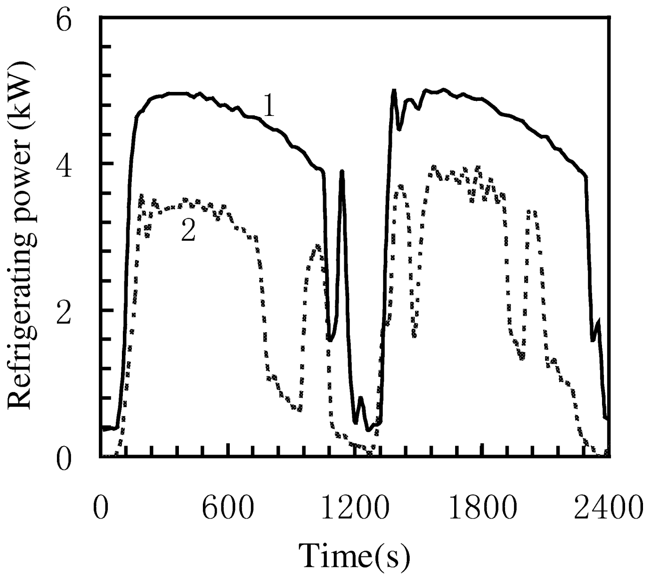

Fig. 12. Refrigerating power vs. time for different cooling water temperatures, 1—21 °C, 2—27 °C, the other operation parameters are $T_{\text{heat,s}} = 100\,°\text{C}$, $t_{\text{cycle}} = 40$ min, $t_{\text{reg}} = 120$ s.

7. Conclusion

The influence of cycle time, heat source temperature, evaporating temperature, stroke of throttling valve and cooling water temperature on operating process in the continuous heat recovery adsorption refrigerator are analyzed by means of experiments. The operation characteristics of the system are realized. For this system, when the cycle time is 40 minutes and the heat source temperature is 100 °C, a better COP and SCP can be obtained. In addition, role of the throttling valve is realized from analysis of experimental data.

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