DYNAMIC ANALYSIS OF HEAT RECOVERY PROCESS FOR A CONTINUOUS HEAT RECOVERY ADSORPTION HEAT PUMP

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ABSTRACT

Heat recovery cycle plays an important role in improving operation performance of a continuous heat recovery adsorption heat pump. The actual heat recovery ratio would be less than the ideal value because of limited heat transfer coefficient of the adsorber. In this paper, by the dynamic calculation of a continuous heat recovery adsorption heat pump, heat recovery ratio in different working conditions was determined. Meanwhile the influence of adsorber heat transfer coefficient was analyzed, and the influences of system operation parameters, such as heat source temperature, cooling water temperature, cycle time and so on, on heat recovery process were also analyzed. The way to increase usable heat recovery effect was discussed.

KEYWORDS

adsorption heat pump, heat recovery, dynamic analysis

1. INTRODUCTION

Heat recovery cycle plays an important role in increasing operation performance for a continuous adsorption heat pump. Heat recovery cycle can increase performances of the system. Many experts have taken the research, for example, the thermal-wave cycle developed by Shelton[1] might recover heat very effectively. Pons[2] also considered recovering the heat in design of an adsorption heat pump. Douss and Meunier[3-5] analyzed the available heat for an adsorption system that uses many adsorbers, and pointed out that the more adsorbers are used, the more heat recovery would be obtained. Theoretically, there is a lot of usable heat which can be recovered for the system with two adsorbers. This heat includes the sensible heat which reject from adsorber's materials and heat rejected during adsorption process. But the usable heat recovery capacity would be decreased in real operation, because of the limitation of the heat transfer coefficient of the adsorber. Therefore the methods of dynamic analysis must be adopted to determine real usable heat recovery capacity and to analyze the way to increase usable heat recovery capacity.

In this paper, the dynamic process of heat recovery is analyzed. Relation of heat recovery time and system operation performance is discussed.

2. DESCRIPTION OF HEAT RECOVERY PROCESS

2.1 Description of a continuous heat recovery adsorption heat pump

Recently, we have developed a continuous heat recovery adsorption heat pump using actived carbon-methanol[6]. Fig.1 shows the schematic of the system.

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. Another adsorber adsorbs refrigerant vapor from the evaporator under low temperature and low pressure. In this way, refrigerant inside the evaporator keeps evaporating which causes refrigerating effect. If the two adsorbers desorbe and adsorbe alternatively, the continuous refrigerating can be obtained. The second part includes a condenser, a flow control valve and an evaporator. After the refrigerant vapor under high temperature and high pressure is cooled in the condenser. Then it goes through the flow control 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.

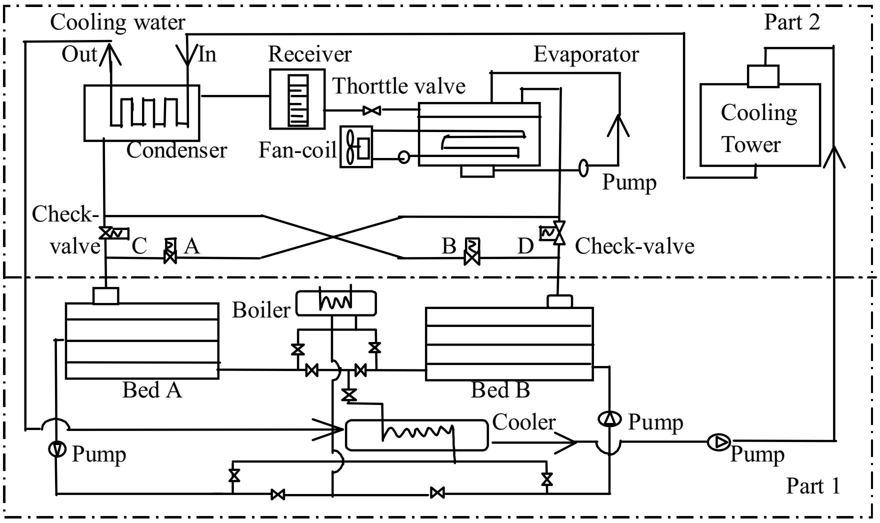


Figure 1 Schematic of the continuous heat recovery adsorption heat pump

In the experimental prototype, heat input to the system was provided by a 30kW electric boiler, which provides hot water from 70°C to 110°C. The adsorber and the condenser are cooled by cooling water from a water cooling tower. The refrigeration effect is output to two fan-coils by chilled water circulation. In the system, the two adsorber are designed based on shell-tube heat exchangers with a heat transfer coefficient of $90W/m^2 {}^\circ C$[7]. The condenser used is a plate type heat exchanger. The evaporator is a spray type one.

2.2 Heat recovery cycle of the system

For an adsorption heat pump, two adsorbers or more should be used in order to produce continuous refrigerating effect. For the system with two adsorbers, when the adsorbers complete one process and start to change their working states, the adsorber that has just finished desorbing process will be cooled down so that it will release a lot of heat. Meanwhile the adsorber that has just finished adsorbing process will be heated so that it needs a lot of heat. Therefore, heat discharged by the adsorber to be cooled can be partly recovered, and thus used to heat the another adsorber if they are connected together. This process is known as heat recovery process.

Dynamic description of a heat recovery cycle: when desorbing process of adsorber A and adsorbing process of adsorber B are completed, adsorber A and the heat transfer medium inside adsorber A are at desorption temperature, meanwhile adsorber B and the heat transfer medium inside are at adsorption temperature. By the opening and closing of the valves, the heat transfer mediums of the two adsorbers are connected, then high temperature and low temperature mediums are mixed up to a go-between temperature. The high temperature adsorber transfers its heat to the low temperature adsorber through the flow of thermal medium. In the p-t-x diagram (see Fig. 2), for an ideal stable operation, the ideal recoverable heat includes: (1) the sensible heat discharged by adsorber materials, adsorbent and adsorbate in the adsorber when temperature decreases from T_{g2} to T_{a2} , and from T_{a2} to T_{e1} ; (2) the adsorption heat discharged during adsorbent adsorbing when adsorbent temperature decreases from T_{a2} to T_{e1}.

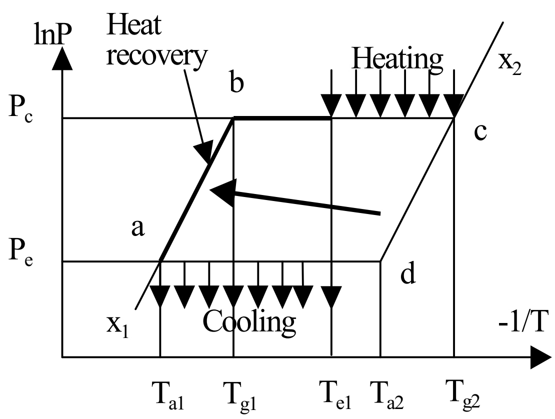


Figure 2 p-t-x diagram of ideal cycle for two adsorbers

But in the operation of a real system, heat release of the high temperature adsorber and heat absorbency of low temperature one is limited owing to the limitation of the heat transfer coefficient of the adsorbers. Therefore the selection of heat recovery time is very important in recovery of heat. Dynamic equations of the adsorption heat pump were shown in the literature [7].

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

COP is calculated as

$$COP = Q_{ref} / \Delta W \qquad (1)$$

where Q_{ref} is refrigerating capacity in one cycle (kJ), ΔW is the used electric energy in one cycle (kJ).

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

$$SCP = \left[1000 \cdot Q_{ref} / \left(t_{cycle} \cdot 60\right)\right] / M \qquad (2)$$

in which *M* is the mass of adsorbent in one adsorber (kg). In this adsorption heat pump, each adsorber was filled with 26kg. t_{cycle} is the cycle time of the system operation (min).

3 SELECTION OF SYSTEM HEAT RECOVERY TIME

3.1 Analysis on heat recovery performance

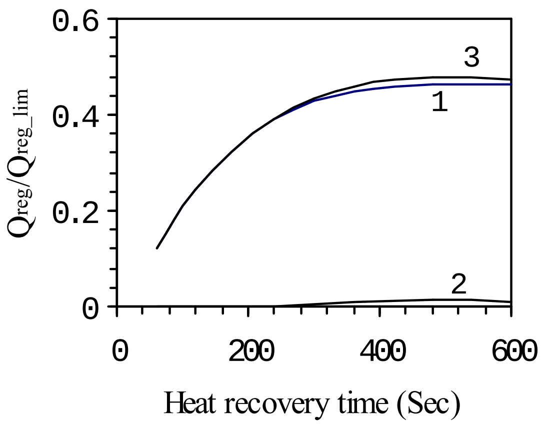
In a continuous heat recovery adsorption heat pump system, heat recovery cycle plays an important role in improving the system's COP (Coefficient of Performance). For example, in one cycle of the system, under the working condition with 100°C heat source, 21°C cooling water and 9.5°C evaporating temperature, the limit usable heat recovery capacity Q_{reg_lim} is 10460kJ, in which the usable sensible heat Q_{reg_s} of the adsorber take up 55% and the usable adsorption heat Q_{reg_a} takes up 45%. In this case, the heat output of the boiler is 19900kJ. However, in the real system, real heat recovery is much less than the ideal value because of limitation of the heat transfer coefficient of the adsorber.

Being limited by adsorber heat transfer coefficient, recovery of adsorption heat during adsorption process becomes very difficult. The reason is that adsorption heat can be used only when adsorber's temperature decreases to T_{a2} and adsorbing process begins with adsorber connected with evaporator. But it takes some time for adsorber's temperature to decrease down from T_{g2} to T_{a2}. Therefore, when the adsorber's temperature begins to decrease and ranges between T_{g2} to T_{a2}, all heat recovered is sensible heat. The less the heat transfer coefficient of adsorber is, the longer the time it takes for adsorber's temperature decreasing down to T_{a1}. In order to know the relationship between heat recovery time and heat recovery capacity, dynamic equation is used here to calculate the system's heat recovery cycle. In all calculation, the heat transfer coefficients of the two adsorbers are 90W/m^2°C which is based upon experimental results[7]. Fig. 3 shows the relationship between heat recovery time and the usable heat recovery ratio of adsorber.

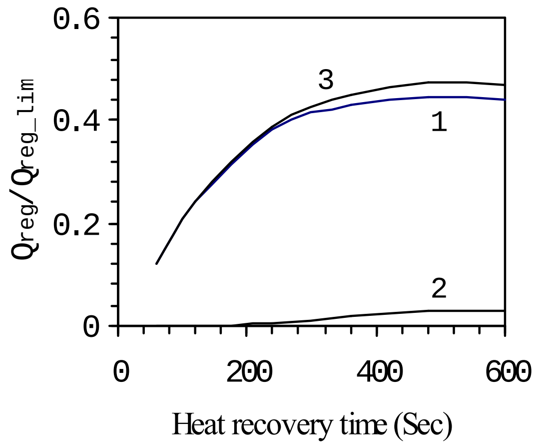
Fig.3(a) shows that when heat recovery time is 240 seconds, the sensible part of recoverable heat has reached up to 39% of the limit usable heat recovery capacity. With extending of heat recovery time, the increasing speed of heat recovery ratio reduces gradually, and finally reaches a maximum value-46.4%. Recovery of adsorption heat takes up very small proportion of the total heat recovery, and furthermore, heat recovery time must be more than 240 seconds, adsorption heat can be obtained and maximum usable adsorption heat recovery ratio takes up only 1.33%. Thus, it is very difficult to fully utilize adsorption heat in this system.

The recovery ratio of adsorption heat is related not only to heat recovery time, but also to system operation parameters, which includes heat source temperature $T_{heat,s}$, cooling water temperature T_{cool}, cycle time t_{cycle} and evaporating temperature T_e, etc.

If the heat source temperature increases, the final desorbing temperature of adsorber will also increase. If the final adsorbing temperature is not changed, both of temperature-up and temperature-down rates of the adsorbers during adsorber heat recovery process will be increased owing to the increase of the temperature difference of the two adsorbers. Therefore, there will be more adsorption heat to be recovered. When the heat source temperature increases, calculations with another group of working conditions are made. The result is shown in Fig. 3(b). The adsorption heat recovery ratio is increased a little bit, and the maximum usable adsorption heat recovery ratio takes up 2.9%. The maximum usable sensible heat takes up 44.4% of the limit usable heat recovery capacity, slightly drop. Therefore, if the heat source temperature is increased, the usable heat recovery capacity will take basically the same proportion of the limit usable heat recovery capacity.



(a) $T_{heat,s}$=100°C



(b) $T_{heat,s}$=120°C

Figure 3 Ratios of the usable sensible heat of adsorber materials, the usable adsorption heat and all of the usable heat recovery capacity to the limit usable heat recovery capacity, 1-$Q_{reg,s}/Q_{reg\_lim}$, 2-$Q_{reg,a}/Q_{reg\_lim}$, 3- $(Q_{reg,s}+Q_{reg,a})/Q_{reg\_lim}$, the other operation parameters are T_{cool}=21°C, t_{cycle} =40min, T_e=9.5°C

The cooling water temperature affects adsorbing temperature and condensing temperature of the system, thus affects the usable heat recovery capacity. Fig.4 shows data when system operating under working conditions with 27°C cooling water. In this group of data, adsorption heat recovery ratio takes up nearly to zero and the proportion of the usable sensible heat is increased. This is mainly because of the increase of cooling water temperature which results in rising of final adsorbing temperature, and thus the limit usable heat recovery capacity is reduced. Therefore, the sensible heat recovery capacity takes up more proportion, and when heat recovery time is 240 seconds, the usable heat recovery ratio will take up 45.2%, and the maximum usable heat recovery ratio will take up 56%.

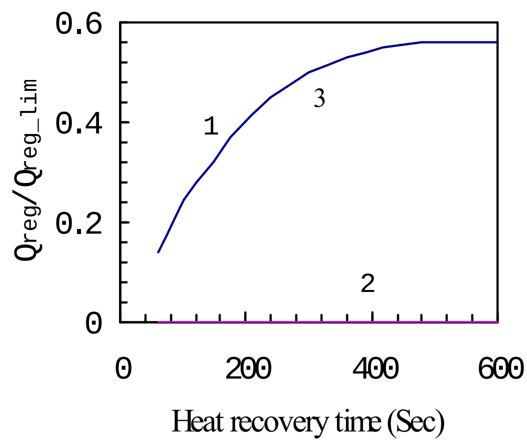


Figure 4 Ratios of the usable sensible heat of adsorber materials, the usable adsorption heat and all of the usable heat recovery capacity to the limit usable heat recovery capacity, 1-$Q_{reg,s}/Q_{reg\_lim}$, 2-$Q_{reg,a}/Q_{reg\_lim}$, 3- $(Q_{reg,s}+Q_{reg,a})/Q_{reg\_lim}$, the other operation parameters are $T_{heat,s}$=100°C, T_{cool}=27°C, t_{cycle} =40min, T_e=9.5°C

The above analyses show that it is very difficult to recover the adsorption heat in this system. One effective way is to increase the heat transfer coefficient of the adsorber, so as to speed up the adsorber's temperature decreasing rate. The effect of the heat transfer coefficient of the adsorber α on heat recovery ratio is shown in Fig.5. In comparison with α=90W/m^2·°C , if α increases from 90 to 120W/m^2·°C (see Fig.6(a)), and the heat recovery time is 2 minutes, the usable heat recovery ratio will increase 7.4%. When heat recovery time is 4 minutes, the usable heat recovery ratio will increase 8.1%. If total heat transfer coefficient of the adsorber increase up to 150W/m^{2}·°C (see Fig.6(b)), and the heat recovery time is 2 minutes, the usable heat recovery ratio will increase 14.4%, if the heat recovery time is 4 minutes, the usable heat recovery ratio will increase 14.9%. But the usable adsorption heat is still very low, only with a maximum value of 6.8%.

Furthermore, the following phenomenon is found in the calculation: when the temperature of one adsorber starts to decrease, the heat released by the adsorber only includes the sensible heat of the adsorber so that the temperature of the adsorber can decrease quickly. When the adsorber starts adsorption process, the heat released by the adsorber includes not only the sensible heat but also adsorption heat. In this case, the recovery of the sensible heat is limited by the recovery of adsorption heat so as to slow the speed of the temperature decrease in the adsorber, because of the limited heat transfer of the adsorber.

Therefore, with extending of heat recovery time, the recovery of adsorption heat will increase, but the recovery of the sensible heat will decrease so that there isn't a larger increase for the recovery of all the usable heat.

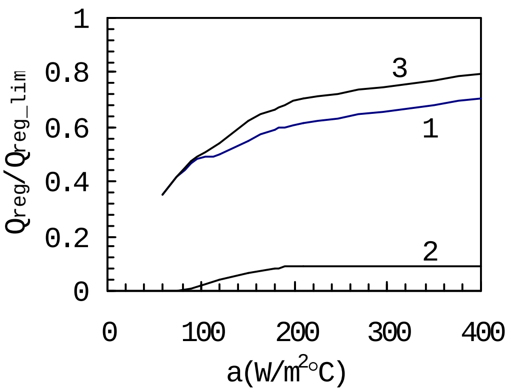


Figure 5 Heat transfer coefficient of the adsorber and the usable heat recovery ratio, 1-$Q_{reg,s}/Q_{reg\_lim}$, 2- $Q_{reg,a}/Q_{reg\_lim}$, 3-($Q_{reg,s}$+ $Q_{reg,a}$)/Q_{reg_lim}, the other operation parameters are t_{reg}=10min

3.2 Heat recovery time and system operation performances

For a system operation, heat recovery time should be selected upon the considerations of heat recovery capacity (i.e., increasing system COP), and also specific cooling power (SCP). Some calculations were made to know the relation between heat recovery time and system operation performances SCP, COP. Fig. 7-9 shows the system operation performances under different heat source temperatures, different cycle times, and different cooling water temperatures.

During the heat recovery process, the adsorber at high temperature transfers its heat to the adsorber at low temperature. The temperature difference of two adsorbers decreases gradually. Thus, the cooling speed of the adsorber is slower than that of the adsorber cooled by the cooling water directly. Namely, with heat recovery process, it takes more time that the pressure of the adsorber decreases to the evaporating pressure to start adsorption process. Similarly, with heat recovery process, it takes more time that the pressure of the adsorber increases to condensing pressure to start desorption process. Therefore, the SCP is reduced gradually with the increasing of heat recovery time, shown as Figs.7-9. In addition, Fig.8 shows that there is a larger influence of the cycle time on the decreasing rate of SCP vs. heat recovery time. But Fig.7 and Fig.9 show that there is a little influence of heat source temperature and cooling water temperature.

For COP, there is a maximum value with the increase of heat recovery time. Figs.7-9 show that COP increases gradually with the increase of heat recovery time, then reaches a maximum value, and then begins to reduce. Usually, in the same working condition, the less the heat recovery is, the more heat output of a heat source is. Thus, in a certain cycle time, with the increase of a heat recovery time, the heat output of the heat source decreases gradually and the refrigerating capacity decreases a few. But if the heat recovery time is too long, the heating time and cooling time of adsorbers will be shortened so that there is not enough adsorption/desorption time to make the refrigerating capacity decrease in a certain cycle time. Fig.8 shows that there is a lager decrease rate of COP vs. the heat recovery time for the shorter cycle time. Therefore, the short heat recovery time must be selected for the condition of the shorter cycle time. The short heat recovery time should be also selected to guarantee a high SCP of the system.

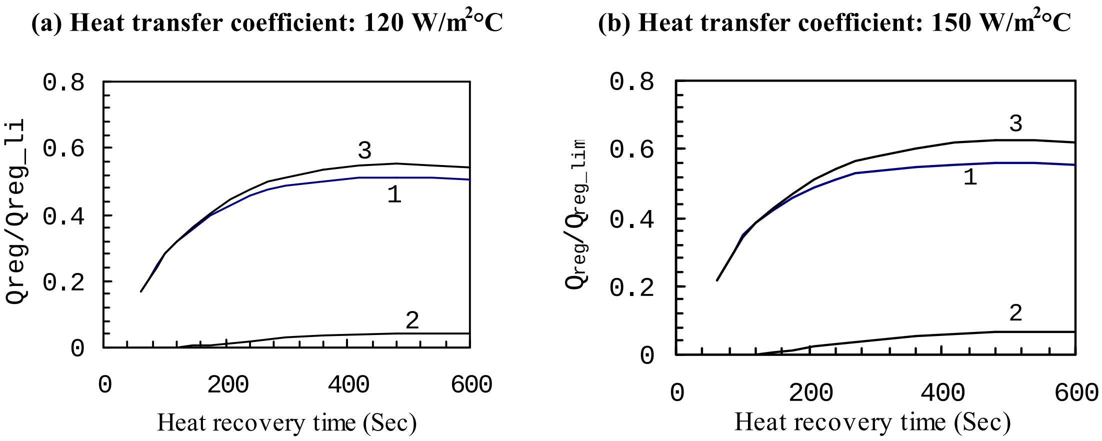


Figure 6 Ratios of the usable sensible heat of adsorber materials, the usable adsorption heat and all of the usable heat recovery capacity to the limit usable heat recovery capacity, 1 - $Q_{reg,s}/Q_{reg\_lim}$, 2- $Q_{reg,a}/Q_{reg\_lim}$, 3- $(Q_{reg,s}+ Q_{reg,a})/Q_{reg\_lim}$, the other operation parameters are $T_{heat,s}$=100°C, T_{cool}=21°C, t_{cycle} =40min, T_e=9.5°C

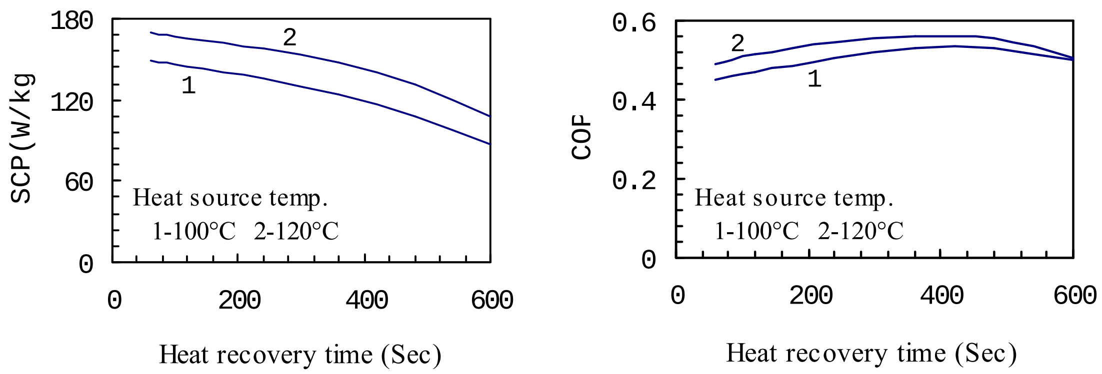


Figure 7 Heat source temperature and heat recovery time vs. SCP and COP, the operation parameters are T_{cool}=21°C, t_{cycle} =40min, T_e=9.5°C

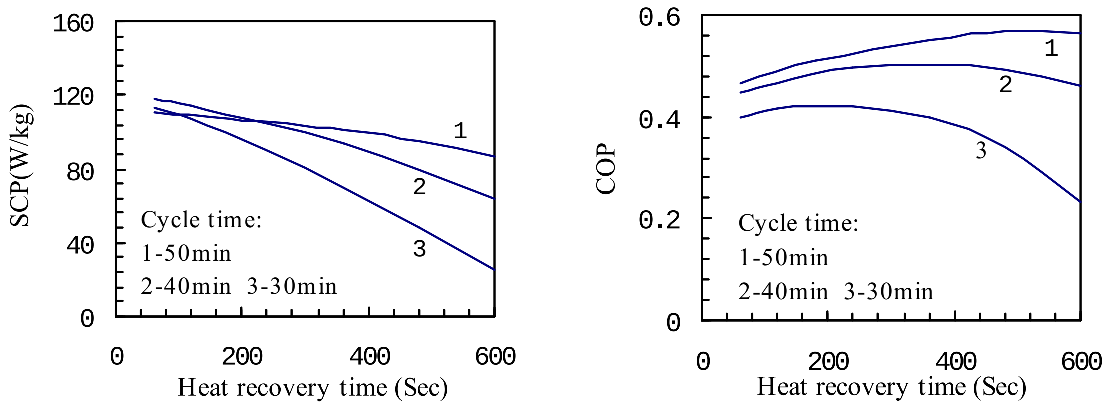


Figure 8 Cycle time and heat recovery time vs. SCP and COP, the operation parameters are $T_{heat,s}$=100°C, T_{cool}=27°C, T_e=9.5°C

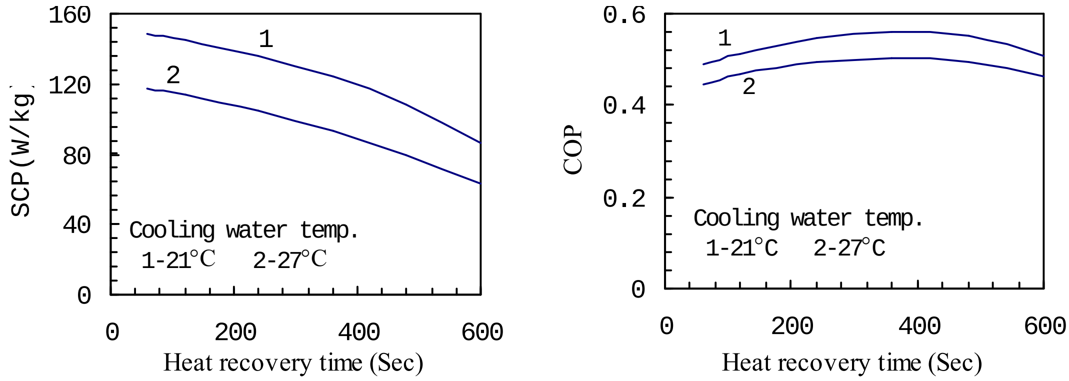


Figure 9 Cooling water temperature and heat recovery time vs. SCP and COP, the operation parameters are $T_{heat,s}$=100°C, t_{cycle} =40min, T_e=9.5°C

4. CONCLUSIONS

It can be concluded by the above analyses that in real system, recovery of adsorption heat is very difficult due to the limitation of heat transfer coefficient of the adsorber. In addition, adsorption heat recovery may also limit sensible heat recovery of adsorber. Therefore, in a operation of a heat recovery process, adsorption heat recovery might not be considered. During the whole heat recovery process, valves connecting adsorber with evaporator should be shut off to decrease adsorber temperature quickly and to recover sensible heat of adsorber.

ACKNOWLEDGEMENTS

This work was supported by the state Key Fundamental Research Program under the contract No. G2000026309. This work was also supported by the Teaching and Research Award Program for Outstanding Young Teachers in High Education Institutions of MOE, China.

REFERENCES

1. Sam V. Shelton, William J. Wepfer and Daniel J. Miles, Square wave analysis of the solid-vapor adsorption heat pump, Heat Recovery Systems & CHP, 1989, 9(3):233-247, ISSN 0890-4332(1989)
2. M.Pons and S.Szarzynski, An adsorption cooling system with heat-regeneration: experimental and numercal study, Proceeding of the International Sorption Heat Pump Conference, Germany, March 24-26, 1999: 625-630
3. N.Douss.L.M.Sun and F.Meunier, Predictive model and experimental results for a two-adsorber solid adsorption heat pump, Industrial & Engineering Chemistry Research, 1988, 27(2):310-316, ISSN 0888-5885 (1988)
4. F.Meunier, Second law analysis of adsorptive heat pump operating on cascade, Heat recovery Systems & CHP, 1986(5):133-141, ISSN 0890-4332 (1986)
5. N.Douss, F.Menuier, Experimental study of cascading adsorption cycles, Chemical Engineering Science, 1989, 44:225-235, ISSN 0009-2509 (1989)
6. R.Z.Wang, J.Y.Wu, Y.X.Xu, W.Wang, Performance researches and improvements on heat regenerative adsorption refrigerator and air conditioning, Energy Conversion and Management, 2001, 42(2):233-249, ISSN 0196-8904 (2000)
7. J.Y. Wu, R. Z. Wang, Y.X.Xu, Dynamic simulation and experiments of a heat regenerative adsorption heat pump, Energy Conversion and Management, 2000, 41(6):1007-1018, ISSN 0196-8904 (2000)

NOMENCLATURE:

COP	Coefficient of performance;
M	Mass of adsorbent in one adsorber, kg
Q_{ref}	Refrigerating capacity in one cycle, kJ
$Q_{reg,s}$	Usable sensible heat of adsorber in one cycle; kJ
$Q_{reg,a}$	Usable adsorption heat in one cycle; kJ
Q_{reg_lim}	Limit usable heat recovery capacity in one cycle; kJ
SCP	Special cooling power; W/kg
$T_{heat,s}$	Heat source temperature; °C
T_{cool}	Cooling water temperature; °C
T_e	Evaporating temperature; °C
t_{cycle}	Cycle time; min
t_{reg}	Heat recovery time; min
ΔW	Used electric energy in one cycle, kJ
a	Heat transfer coefficient of adsorber; $W/m^2 °C$