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PERFORMANCE IMPROVEMENT OF ADSORPTION HEAT PUMP BY HEAT AND MASS RECOVERY OPERATIONS

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Abstract

An adsorption heat pump was developed and tested, various operation procedures have been tried, the experimental results show that the heat recovery operation between two adsorption beds will increase COP for about 25% if compared with one adsorber basic cycle system. It was also proved that mass recovery is very effective for heat recovery adsorption heat pump operation, which may help to get a COP increase for more than 10%.Theoretical analyses have been done, in which the COP for a basic intermittent adsorption cycle, a continuous two-adsorber heat recovery cycle, mass recovery cycle, mass recovery with sensible heat recovery, mass recovery with both sensible heat and heat of adsorption recovery, have been specially studied. The theoretical results are in good agreement with experimental values. Based upon the developed theoretical model, it is possible to predicate the COP for various operation procedures of a real adsorption heat pump.

KEYWORDS:

adsorption, heat pump, air conditioning, heat recovery, mass recovery

INTRODUCTION

Adsorption refrigeration with different cycles have been studied extensively, the typical adsorption refrigeration cycles are (1)basic cycle, which is an intermittent refrigeration cycle if operated with one bed. Continuous refrigeration can be only achieved with two or more beds to shift the heating-cooling phases. In a basic cycle, there are no heat recovery; (2) Continuous heat recovery cycle, which is usually operated with two adsorption beds, the adsorber to be cooled will transfer its heat to the adsorber to be heated, the heat transfer between two beds includes sensible heat and heat of adsorption. This heat recovery process is meaningful to increase COP. Multi-beds could be also adopted to get more heat recovery and thereby much higher COP; (3)thermal wave cycle [1], which is assumed that a big temperature gradient exists along an adsorption bed, for a two beds system, high temperature thermal fluid flows into the adsorber, exchanges heat with the bed, and the temperature goes down along the bed rapidly, thus the outlet temperature will be close to ambient. After cooled by ambient surroundings, the fluid flows into another adsorption bed, absorbes heat from the bed, and the temperature of the fluid goes up, at the exit of this bed, the thermal fluid temperature will be very close to the temperature of heat source . In this case, only small heat is added into the system, and very small heat released to the environment, thus heat recovery ratio is prettily high, COP is of course significantly increased. (4) convective thermal wave cycle [2], the concept is the same as thermal wave cycle, however the thermal fluid for heating or cooling to the beds is initiated by the refrigerant itself, thus the heat transfer between thermal fluid and adsoption bed is direct contact heat transfer, which is incorporated with mass transfer in the system. (5) cascading cycle [3,4], in which zeolite-water /activated carbon-methanol, or, zeolite-water/silica gel-water, and zeolite-water/zeolite-water are usually used for cascading, the high temperature heat source (eg. 200 ^{o}C) is used to drive high temperature stage adsorption refrigeration cycle (typically 100 –200 ^{o}C for zeolite-water), the low temperature stage adsorption refrigeration is driven by the sensible heat and heat of adsorption of high temperature stage, for example, activated carbon-methanol or silica gel-water adsorption refrigeration cycles are suitable for generation temperature of 100 ^{o}C, which are operated between 30 –100 ^{o}C.

The above adsorption refrigeration cycles have been convinced by various researchers. Basic cycle is easy to apply, which is very suitable for solar refrigeration and also waste heat recovery refrigeration. Heat recovery cycle is practical as the system has reasonable COP and is not so complicated. Thermal wave cycle is attractive, however it needs very high thermal conductivity which is not easy for adsorbents to reach, in addition the thermal fluid velocity is confined which reduces the specific cooling power [5]. Convective thermal wave cycle is reasonable in theory, however not so convenient to build the real system. Cascading cycle is attractive to have high COP, but the system will be much complicated [4].

For real applications, heat recovery two beds system is well accepted, however one need to increase its COP and specific cooling power (SCP) significantly. The various operation procedures will influence the system performances obviously, specially the mass recovery operation, which is just the two beds connection to yield equilibrium pressure between two beds before heat recovery, this process will enlarge the desorbed refrigerant mass, and thereby increase refrigeration effect, and possibly have a increased COP. This paper shows the detailed mass recovery theory and its applications in experiments of a two beds adsorption air conditioning system.

HEAT RECOVERY ADSORPTION REFRIGERATION CYCLES

Adsorption refrigeration is based upon the processes of heating-desorption-condensation and cooling-adsorption-evaporation, the cooling-adsorption process needs heat dissipation both of sensible heat and heat of adsorption. A two beds continuous adsorption refrigeration system with heat recovery is shown in Fig.1. Heat recovery is important to increase the cycle COP, the possible heat recovery for a two adsorption bed system will be some part of sensible heat and heat of adsorption shown as fig.2.

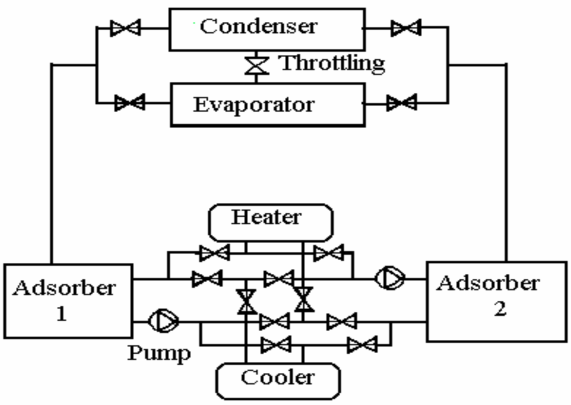

Fig.1 Schematics of heat recovery two-beds adsorption refrigeration system.

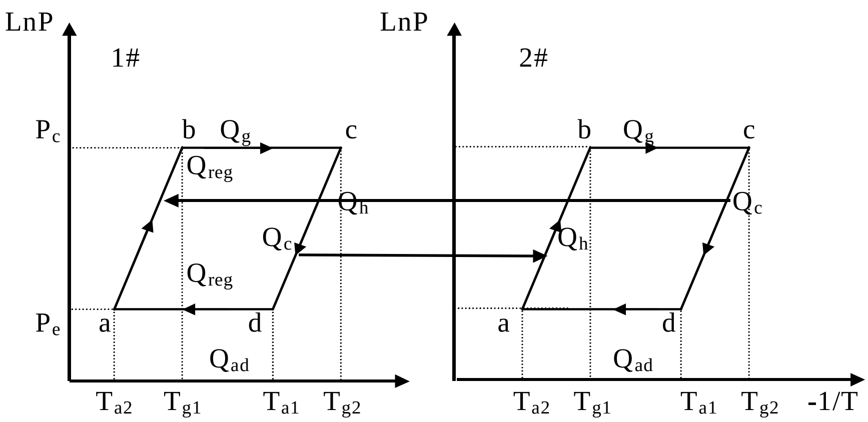

Fig.2 Two-bed adsorption system with heat recovery.

The COP for basic type adsorption refrigeration cycle (one bed or two beds without heat recovery) is

$$COP_B = \frac{Q_{ref}}{Q_h + Q_g} \tag{1}$$

The COP for a two-bed heat recovery cycle can be expressed as

$$COP = \frac{Q_{ref}}{Q_h + Q_g - Q_{reg}} \tag{2}$$

Where Q_{reg} is the heat recovered. In the above equations, Q_h and Q_g are the heat for generation corresponding the two processes (isostersis and isobars). The refrigeration effect

$$Q_{ref}=\Delta x \cdot L \tag{3}$$

is the latent heat L multiplied by the cycle concentration change Δx.

The detailed calculation method have been shown in the early work [6], the calculation in this paper is based upon adsorption refrigeration pair, activated carbon – methanol, in which Shanghai YK activated carbon made from coconut shell is used. The fundamental adsorption data can be found in literatures [7,8].

As shown in fig.3, the cycle COP will be increased more than 25% by heat recovery process, but the COP for a single effect refrigeration system is still low, possibly in the range of 0.4 – 0.7. Multi-beds system will be good to recover more heat, thereby increase COP, however the real system will be very complicated.

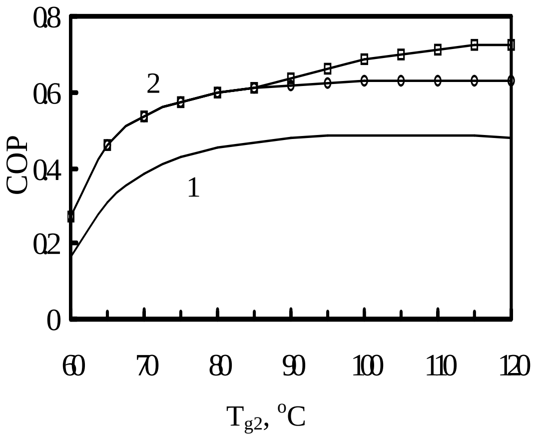

Fig.3 COP with and without heat recovery (Te=5 °C, Ta=Tc=30 °C), 1-basic type cycle, 2-heat recovery cycle (o-sensible heat recovery, □-sensible + adsorption heat recovery)

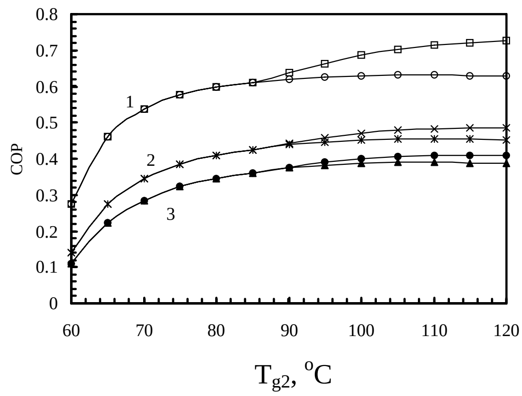

Fig.4 Heat capacity ratio effect on COP of a heat recovery system.1-no consideration of the heat capacity of adsorber material and thermal fluid, R=0; 2- R=1.85; 3- R=2.9.

For a real heat recovery adsorption system, the heat capacity of metallic adsorber and also the thermal fluid will have strong influence on system COP. If R_m is defined as the heat capacity ratio of adsorber material to adsorbent, and R_f that of thermal fluid to adsorbent, the total heat capacity ratio $R=R_m+R_f$ will have strong influence on system COP. A typical example of the heat capacity ratio effect on system COP is shown in fig.4. It is obvious that the COP decreases significantly if the ratio R increases. For example, when R=2.9, the COP will decrease by 40% if compared with the ideal COP_0 (COP corresponding to R=0) . When R=1.85, the COP decreases about 25-30%. The above two examples are related to the prototype adsorption heat pump.

In real design of an adsorption system, good heat transfer should be considered, in order to shorten cycle time and increase specific cooling power (SCP), which may need to increase heat transfer area by finned tubes etc.. But the heat capacity ratio should be controlled, the ideal value of R should be limited below 5, possibly below 3. Oil should be used as thermal fluid to decrease the heat capacity ratio R_f, also the flow volume of thermal fluid should be controlled.

HEAT AND MASS RECOVERY ADSORPTION REFRIGERATION CYCLE

A normal two bed heat recovery system can be demonstrated in Fig.5 in one p-T-x diagram (if compared with Fig.2). Mass recovery could be initiated before heat recovery (the ideal heat recovery state will be e-e' for a two bed system shown in Fig.5). As is clear, when adsorber 1 (as generator) is desorbed, it is at the generation temperature T_{g2} and condensing pressure P_c, which is to be cooled to serve as adsorber (temperature from T_{g2} to T_{a2}, pressure from P_c to P_e), while adsorber 2 (currently as adsorber) has adsorbed refrigerant, and is hoped to be heated to serve as generator (temperature from T_{a2} to T_{g2}, pressure from P_e to P_c). A go-between connection between two adsorbers will speed up the pressure changes to reach equilibrium pressure $P_m=(P_e+P_c)/2$. This process will cause more desorption in the generator shown as fig.6. As is shown in fig.7, the operation for a two bed mass recovery can be easily achieved by the connection of adsorber 1 and adsorber 2 via a valve.

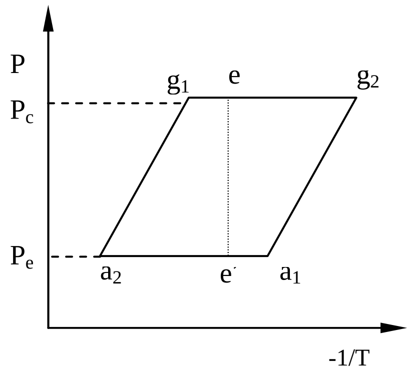

Fig.5 diagram of the intermittent and heat recovery cycle.

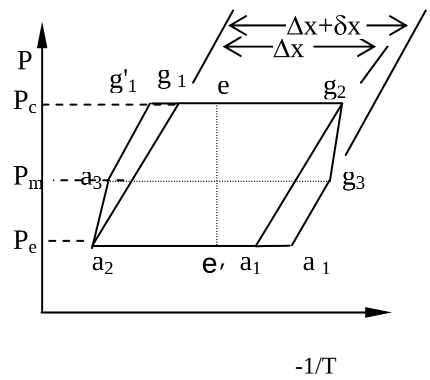

Fig.6 diagram of mass recovery cycle and heat and mass recovery cycle.

The mass recovery cycle (a_2-a_3-g_1'-g_1-g_2-g_3-a_1'-a_2) extends the two bed basic cycle or two bed heat recovery cycle (a_2-g_1-g_2-a_1-$a_2$showns as fig.6), and the cycle mass is increased from Δx to $\Delta x+\delta x$, which causes the refrigeration effect to increase. If the heat of adsorption and the heat of desorption is the same (at the same pressure), the cycle COP will increase due to the increased refrigeration effect in a cycle.

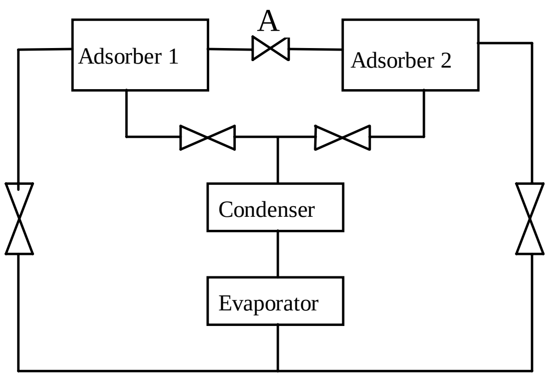

Fig.7 Mass recovery operation between two adsorbers via opening of valve A.

In this discussion the mass recovery process is assumed as adiabatic. The process is divided into two parts operated in two beds as a_2-a_3 and g_2-g_3. The process can be simulated and calculated utilizing the following model.

The vapor desorbed from the high pressure bed are entirely re-adsorbed by the low pressure bed. That is

$$\delta X_{a3-a2} = \delta X_{g3-g2} \tag{4}$$

The beds are adiabatic during this process. The temperature variation is caused by sorption or desorption.

$$(C_{pa}+XC_{pr})(T_{a3}-T_{a2}) = \Delta H \delta X_{a3-a2} \tag{5}$$

$$(C_{pa}+XC_{pr})(T_{g3}-T_{g2}) = \Delta H \delta X_{g3-g2} \tag{6}$$

where C is the specific heat, X is the adsorptivity, ΔH is the heat of adsorption/desorption. The subscripts “a” and “c” represent adsorbent and refrigerant respectively.

The final pressure of the two beds should be equal to each other,

$$P_{g3}=P_{a3} \tag{7}$$

The iterative calculation method could be used by supposing a final pressure at the first $P=(P_c+P_e)/2$, and calculate the temperature and concentration change of each bed. Then modify the supposed pressure if necessary to satisfy eq.(4) until a satisfactory result is derived.

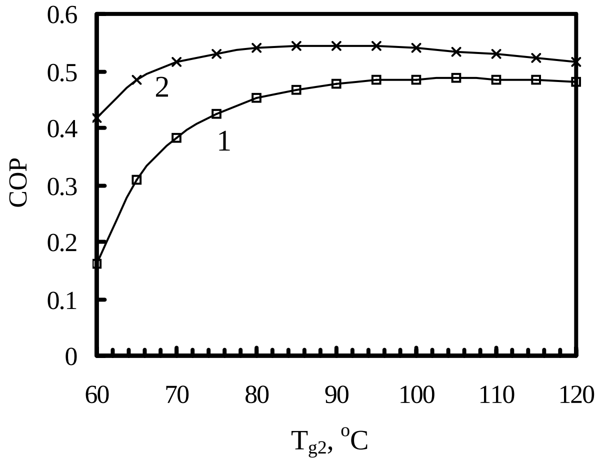

Fig.8 Comparison of COPs for basic type cycle (1) and mass recovery cycle (2). T_e=5^{o}C,T_c=T_a=30 ^{o}C.

The typical comparison of COPs between basic type (two beds but without heat recovery) cycle and mass recovery cycle (two beds without mass recovery) are shown in fig.8. It is seen that mass recovery cycle is practically suitable for low generation temperatures, the enlarged COP is in the range of 10 – 100 %.

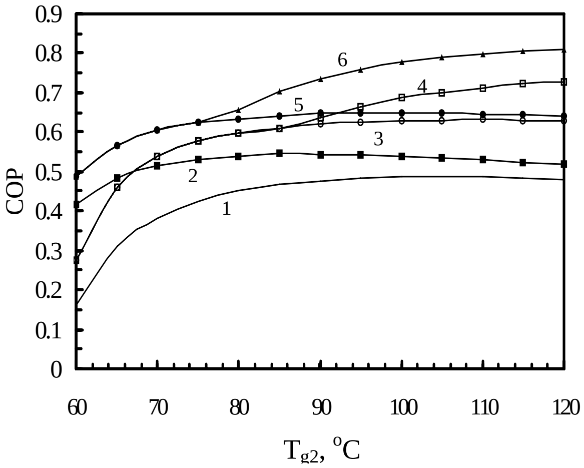

Fig.9 Comparison of COPs for various operation procedures of heat and mass recovery cycle. T_e=5 ^{o}C,T_c=T_a=30 ^{o}C, R=0. 1: Basic type cycle; 2: Mass recovery cycle;3: Sensible heat recovery; 4: Sensible + adsorption heat recovery;5: Sensible heat & mass recovery;6: Sensible + adsorption heat & mass recovery.

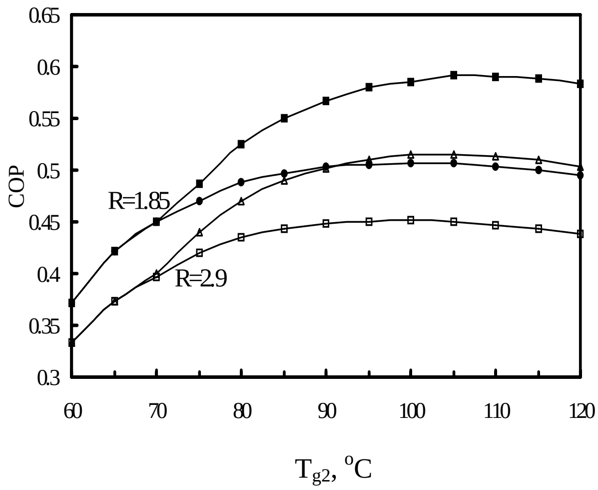

Fig.10 COPs of heat & mass recovery cycles with respect to two different heat capacity ratios at T_e=5 ^{o}C,T_c=T_a=30^{o}C

The mass recovery process is usually before the heat recovery process, the combined mass and heat recovery procedures will contribute COP significantly. In the real system operation, heat recovery may have two kinds. One of which is sensible heat recovery, the other is sensible heat recovery followed by adsorption heat recovery. Fig.9 shows the ideal COPs (for R=0) of various operation procedures compared with basic type cycle and mass recovery cycle. It is seen that mass recovery followed by heat recovery (sensible & heat of adsorption) is of the best performance, and for activated carbon-methanol air –conditioning system, COP over 0.6 can be achieved with a generation temperature of 80 ^{o}C. If the generation temperature reaches 120 ^{o}C, COP will be close to 0.8.

Realistic calculated results for the COPs of mass & heat recovery cycle can be shown in Fig.10, in which two heat capacity ratios R=2.9 and R=1.85 have been assumed. It is seen that the reasonable COP for a real adsorption heat pump can reach close to 0.6.

PERFORMANCES OF AN ADSORPTION HEAT PUMP

An adsorption heat pump for air conditioning using plate fin heat exchangers as adsorbers has been developed in SJTU [9], in which activated carbon - methanol has been used as adsorption pair. Shown as Fig.11, the system has two adsorbers, each of which has 26 kg carbon embedded, the plate fin type adsorber makes the heating and cooling for adsorbers quite quickly. The system can be operated in a cycle time as short as 20 minutes. The cooling is output to a fan-coil (actually two fan-coils each has 5 kW cooling power were used for the experiment) and a cooler is used to cool the thermal fluid of adsorber by cooling water from the cooling water tower.

Due to the big heat capacity ratio (R=11), the system COP is low. As an improvement, a novel type adsorber has been designed, which is a plate finned shell and tube heat exchanger [10], The designed heat capacity ratio between adsorber mass plus thermal fluid and adsorbent bed is 2.9 when water is used as thermal fluid, however good heat transfer is still possible to reach. Two newly adsorbers were installed in the adsorption heat pump system, each of them were also embedded with 26 kg activated carbon.

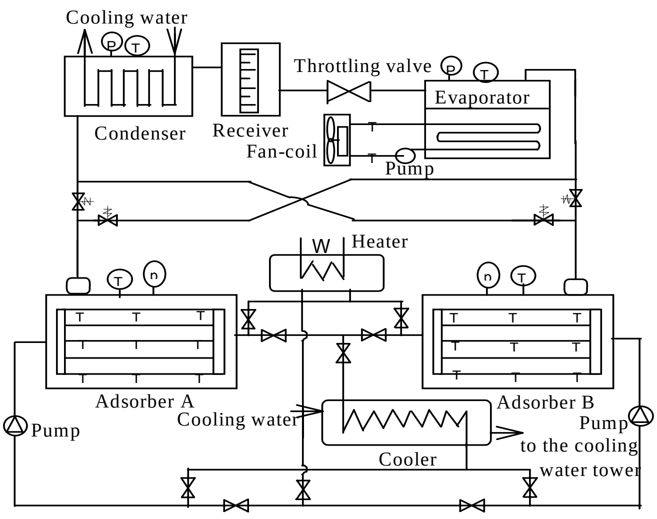

Fig.11 Schematic drawing of the whole adsorption heat pump system.

Some tests were performed to the improved adsorption heat pump with novel configured adsorbers. After various experiments, it was found that the best cycle time for this adsorption heat pump is between 40-50 minutes with a heat recovery time for about 2 minutes. Several typical experiments were done with the following environmental parameters: room temperature:24 ^{o}C, cooling water temperature:23.5 ^{o}C and flow rate of chilled water: 1.157 m^3/hr, thus the performances of the system can be evaluated.

The measuring schemes are: (1) Heat source temperature(T_h):100 ^{o}C, evaporation temperature (T_e):10 ^{o}C, cycle time(t): 50 min; (2) T_h =100 ^{o}C, T_e =10 ^{o}C, t=40 min; (3) T_h =100 ^{o}C, T_e =6 ^{o}C, t=40 min. (4) T_h

=110 ^{o}C, T_e =6 ^{o}C, t=40 min. Various methods have been used to control the evaporation temperature and heat source temperature properly. The cooling power is evaluated by the averaged temperature difference of inlet and outlet of chilled water in the evaporator multiplied by the mass flow rate of the chilled water and the specific heat of water. The COP of the system is evaluated as the cooling capacity divided by the heat input, in which the heat input is counted by an electric kw·hr counter.

Modifications regarding to the heat dissipation of the heating line and boiler to the environment and the heat leak to the evaporator were carried out by experiment, further calculation regarding the difference of heat capacity of thermal fluid between oil and water were also performed (currently water was used as thermal fluid, however oil is the real reasonable fluid for the system). The real system performances with respect to the above four operation conditions are shown in table 1. Table 2 shows the predicted performance of the system based upon experimental results.

The above operation is not completely ideal, heat recovery is effective only for sensible heat, mass recovery have been adopted and was found effective. The further improvement is the heat recovery of adsorption heat. By the way it was observed that thermal conductivity in the bed is very critical, the heat of adsorption was not transferred effectively, the adsorption temperature was about 45 ^{o}C, which is still very high. If the effective heat transfer coefficient in the adsorber was increased, the system performances will be improved significantly.

Table 1 Concluded performances of the adsorption heat pump with respect to four operation conditions

T_h ^{o}C	t min	T_d ^{o}C	T_a ^{o}C	T_c ^{o}C	T_e ^{o}C	Q_f kW	SCP_2 W/kg	SCP_1 W/kg	COP	No
100	50	98.7	46.9	24.0	9.6	3.80	146	159	0.4	1
100	40	96.8	45.6	29.6	9.9	3.93	151	168	0.37	2
100	40	97.8	44.2	26.8	6.1	3.46	133	148	0.34	3
110	40	106	45.7	28.7	6.0	3.70	143	159	0.32	4

* Q_f-averaged refrigeration power, SCP_1-adsorption pair specific cooling power, SCP_2-system specific cooling power.

Table 2 Several measured performances and its prediction after improving insulation and substituting heat medium (water to oil)

Operation Condition Performances	No.1	No.2	No.3	No.4
SCP_{water}	159	168	148	159
COP_{water}	0.40	0.37	0.34	0.32
$SCP_{water, true}$	166	171	151	161
$COP_{water, true}$	0.43	0.40	0.37	0.34
$SCP_{oil, true}$	166	171	151	161
$COP_{oil, true}$	0.50	0.47	0.44	0.39

COMPARISONS AND DISCUSSIONS

The above experimental results are based upon mass recovery operation followed after sensible heat recovery. Theoretical calculation were performed and it is found that good agreement between theory and experiment have reached shown as table 3.

Based upon the experimental work and also the theoretical results shown in Figs. 9-10, it is possible to predicate the maximum COP of the prototype adsorption air-conditioning systems. It is found that with a heat source temperature of 100 ^{o}C, it is possible to achiev COP above 0.5 in real adsorption air conditioning system operated at an evaporation temperature about 5 ^{o}C.

The above work shows clearly that the operation procedures will have a strong influence on the COP of an adsorption air conditioning system, good control is thereby important to yield better performances.

Mass recovery is very simple to operate, but really very effective. For the operation conditions such as high condensing temperatures, low evaporation temperatures, or low generation temperatures, mass recovery operation is strongly recommended. By the way, the thermal capacity ratio between adsorber material & thermal fluid and adsorbent, R, will influence COP obviously, the low R value for a real system will contribute to increase COP significantly if mass recovery is used.

Table 3 Comparisons between theory and experiments for mass & sensible heat recovery and its predication for the maximum COP in operation with full heat & mass recovery.

Experiment	T_{g2} (°C)	T_a (°C)	T_c (°C)	T_e (°C)	COP (Experiment)	COP (Theory)	Predicated maximum COP with full heat & mass recovery	R
No.1	98.7	46.9	24	9.6	0.43	0.46	0.54	2.9
No.2	96.8	45.6	29.6	9.9	0.4	0.43	0.48	
No.3	97.8	44.2	26.8	6.1	0.37	0.41	0.46	
No.4	105.9	45.7	28.7	6	0.34	0.39	0.44	
No.1	98.7	46.9	24	9.6	0.5	0.51	0.62	1.85
No.2	96.8	45.6	29.6	9.9	0.47	0.48	0.55	
No.3	97.8	44.2	26.8	6.1	0.44	0.47	0.53	
No.4	105.9	45.7	28.7	6	0.39	0.45	0.51	

Acknowledgements

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Nomenclature

COP	Coefficient of performance	COP_B	Coefficient of performance for basic cycle
L	Latent heat of vaporization (J)	Q_g	Isobaric generation heat (J)
Q_h	Isotersis heating (J)	Q_{ref}	Refrigeration effect (J)
Q_{reg}	Heat recovered (J)	R	Heat capacity ratio
X	Adsorption capacity (kg/kg)	Δx	Desorbed mass in a cycle (kg/kg)

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