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EXPERIMENTS ON HEAT-REGENERATIVE ADSORPTION REFRIGERATOR AND HEAT PUMP

R. Z. WANG*, Y. X. XU, J. Y. WU AND W. WANG

School of Power and Energy Engineering, Shanghai Jiao Tong University, Shanghai 200030, People's Republic of China

SUMMARY

A heat-regenerative adsorption refrigerator using spiral plate heat exchangers as adsorbers and an adsorption heat pump for air conditioning using plate fin heat exchangers as adsorbers have been developed and researched, experimental research results are shown. The activated carbon–methanol adsorption pair is used for the two adsorption systems, which yield a refrigeration power density of more than 2·6 kg ice per day per kg activated carbon and 150 W kg^{-1} activated carbon for air conditioning, respectively. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: adsorption; refrigerator; heat pump

1. INTRODUCTION

Solid sorption refrigeration (or heat pump) has received increasing attention in recent years; various kinds of sorption refrigerators and heat pumps have been developed, mostly of activated carbon–methanol, zeolite–water, $CaCl_2$–NH_3, and hydride–hydrogen pairs. Intermittent type for solar energy applications (Pons and Guilleminot, 1986), heat regenerative cycle (Douss *et al*., 1988) and cascade system (Meunier and Douss, 1990) have been developed. New thermodynamic cycles, such as thermal wave cycle (Shelton and Wepfer, 1990) and convective thermal wave cycle (Critoph, 1994), have been proposed for possible future potentials. The renewed interests on the studies of adsorption refrigeration are based upon the various advantages of the systems such as non-CFCs problems, cost-effective, simplicity in construction, no need for solution pumps and meanwhile they can be directly driven by low-grade energy.

For real application purposes, the continuous heat regenerative adsorption cycle is usually employed, however, the development of the adsorber is critical. Several types of heat exchangers have been selected as adsorbers (Wang *et al*., 1998) such as shell and tube heat exchanger, flat pipe heat exchanger, flat plate heat exchanger and plate-fin heat exchanger. Recently, we developed spiral plate adsorber and plate fin adsorber, and incorporated into one refrigerator for ice-making and one heat pump for air conditioning, respectively, performance tests have shown good results. Here the developed adsorption systems using activated carbon–methanol pair for both refrigeration and air conditioning purposes are shown, including the experimental results.

*Correspondence to: R. Z. Wang, Director, Research Division for Thermal Environmental Engineering, School of Power and Energy Engineering, Shanghai Jiao Tong University, Shanghai 200030, People's Republic of China

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2. ADSORPTION REFRIGERATOR

A prototype continuous heat regenerative adsorption refrigerator using activated carbon–methanol has been developed, an arrangement of a typical thermal wave type was previously tried; however no good results have been found (Wang *et al.*, 1996). We have improved the adsorption system, in which the two adsorbers are independently operated for heating or cooling along with the intermediate heat recovery process. Figure 1 shows the whole unit and measuring sensors. The system has two adsorbers, one condenser and one evaporator, a receiver is installed for the observation of refrigerant flow in the system. An ice box is used in which it uses salt water as heat transfer fluid to take heat to the evaporator. Figure 2 shows the outlook of the system.

The connections of the two adsorbers to the condenser and evaporator are by four vacuum valves, which keep one adsorber when regenerated being connected to the condenser and the other adsorber when cooled for adsorption connected to the evaporator. Heating to an adsorber is controlled by a computer, the measured data of every sensor are shown on the display of computer.

The adsorber is constructed by two parallel stainless steel welded plates at the two ends, then turned in a spiral line, the bottom end is welded and sealed by a flat plate, while the upper end is faced to a flange to embed adsorbent. The support rod is useful during the spiral-turning process, the space between the turned spiral plate is thus used for adsorbent space. A normal spiral plate heat exchanger has two flow passages, used for heat exchange between fluid 1 and fluid 2; however for a spiral plate adsorber, only one passage is used for thermal fluid flow, the other side passage is sealed and used for the adsorbent bed, the upper plate flange supplies the flow channel for adsorption and desorption processes. The spiral space for an adsorbent bed of 6 kg activated carbon is 18 mm, and the spiral plate area is $2\,m^2$. Twenty stainless-steel screen constructed tubes were inserted into the adsorbent bed for mass transfer improvement purpose.

The above system has been applied for ice-making, which can show its application potentials for waste heat driven ice-maker. We have tried several cycle times such as 40, 60, 80 min, and we found that the indirect refrigerator using salt water as cooling medium is better to apply 40 min cycle time (Wang *et al.*, 1998), for which two working conditions were used for ice-making tests with indirect refrigeration via salt water, Figures 3 and 4 show one 24 h ice-making test for working condition 1 (shown in Table 1), in which the first and the last 5 h test data are shown.

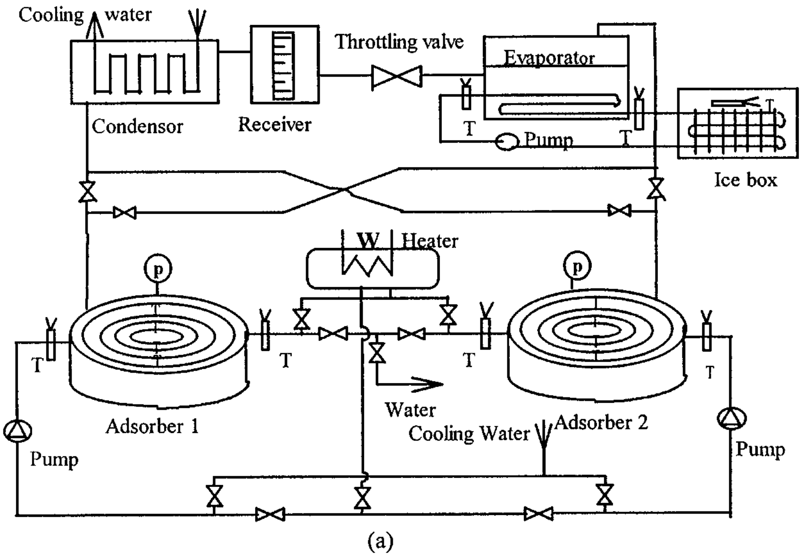


Figure 1. Schematic of a prototype heat-regenerative adsorption refrigerator

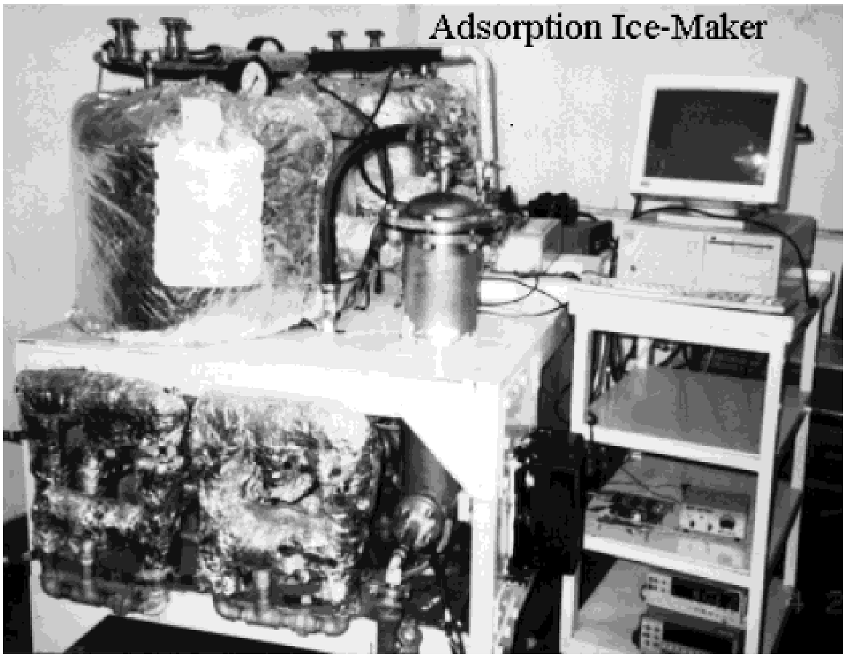
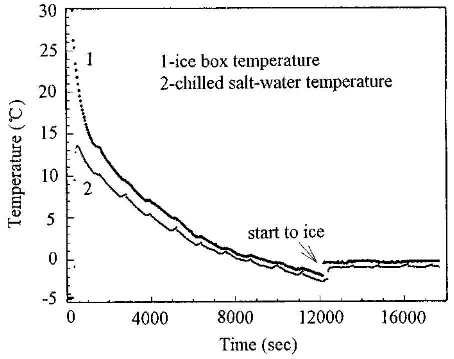


Figure 2. The outlook of the adsorption refrigerator



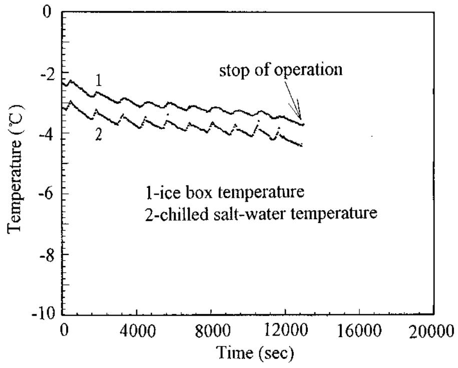


Figure 3. Ice-making test for working condition 1 for the first 5 h test

Figure 4. Ice-making test for working condition 1 for the last 5 h test

After the adsorption refrigerator reached normal operation condition, 15·5 kg water with a temperature of 29·8°C was filled into the ice box, the experimental conditions are: adsorption temperature 25°C, condensing temperature 22°C, evaporation temperature − 15°C, desorption temperature 100°C. The first 5 h refrigeration effect can be shown in Figure 3, in which curve 1 represents measured water temperature in the ice box and curve 2 represents the salt water (coolant) temperature. Figure 3 shows that it takes about 12 000 s to start water–ice transformation, however a sub-cooling is needed to initiate this transformation. During the water–ice transformation period, both of the coolant and water temperature are nearly constant. The last 5 h for the operation is shown in Figure 4, in which the stop point represents 24 h of refrigeration, the remaining water was weighted as 0·9 kg, thus the one day ice made by the machine is 14·6 kg, the ice has a temperature of − 3·7°C.

Table 1. Experimental performance for ice-making with different working conditions

Experimental working condition	Indirect refrigeration			Direct evaporation		
Experimental working condition	1	2	3	4	5	6
Cycle time (min)	40	40	60	80	100	100
Adsorption temperature (°C)	25	30	32	33·5	33	34
Desorption temperature (°C)	100	101·5	91	92	92	97·5
Condensing temperature (°C)	22	30	34·5	35	36·5	34
Evaporation temperature (°C)	− 15	− 13·5	− 15	− 17·5	− 16·5	− 16
Ice made per day (kg)	14·6	13·25	24	26	30	31·5
Refrigeration power density SPD (kg-ice/kg-carbon per day)	1·22	1·10	2	2·17	2·5	2·63

We have noticed that the ice-making system should be improved, specially for the evaporator. The originally applied tube and shell type evaporator with a maximum heat transfer area of 0·5 m^2 in which methanol is evaporated in the shell and salt water in the tube, is not well suited for ice-making purposes (Wang *et al*., 1998), meanwhile a large amount of cooling power was wasted in the pumping salt-water line, we thus improved the system by replacing the indirect refrigeration circuit by a direct evaporator of finned tubes, which yields no refrigeration losses in the coolant (salt water) circuit and is also a good use of heat transfer areas.

A new evaporator has been designed, which is a finned tubes type. The tubes and the fins are ϕ 50 mm and ϕ 100 mm in diameter, respectively, the total heat transfer area is 2·5 m^2 (0·5 m^2 for the tubes and 2 m^2 for the fins) for the evaporator. The big diameter tube is used in order to store the desorbed methanol without 100% filled, thus evaporation can be achieved in every finned tubes to ensure good use of the whole heat transfer area.

The ice-making test results with direct evaporation are shown in Table 1, showing a big improvement! It can be observed though with the low desorption temperature or high condensing and adsorption temperatures! The test results proves that it is possible to achieve a refrigeration power density for ice-making of more than 2·6 kg-ice per day per kg activated carbon. By the way the optimized cycle time is quite different if compared with the indirect evaporation, which is perhaps caused by different heat transfer area and also the difference of heat losses in the evaporator. In this test, the optimized cycle time is 100 min. The COP for ice making test (condition 6 in Table 1) is about 0·12.

3. ADSORPTION HEAT PUMP

An adsorption heat pump for air conditioning using plate fin heat exchanger as adsorbers has been developed, in which activated carbon–methanol has been used as adsorption pair. 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 min. As shown in Figure 5, the system is very close to the adsorption system for ice-making, though 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 adsorption adsorber by cooling water from the cooling tower. Figure 6 shows the outlook of the system.

With the adsorption heat pump we have performed some experiments for air conditioning. Due to a technical problem of one adsorber, operation could only be intermittent without heat recovery between two adsorption beds. Various working conditions have been tested specially for the cycle time and desorption temperature. It has been found that this heat pump can be driven even with a heat source of 60°C, and it is reasonable to have a desorption temperature of about 85–95°C. Different cycle times such as 20, 30, 40,

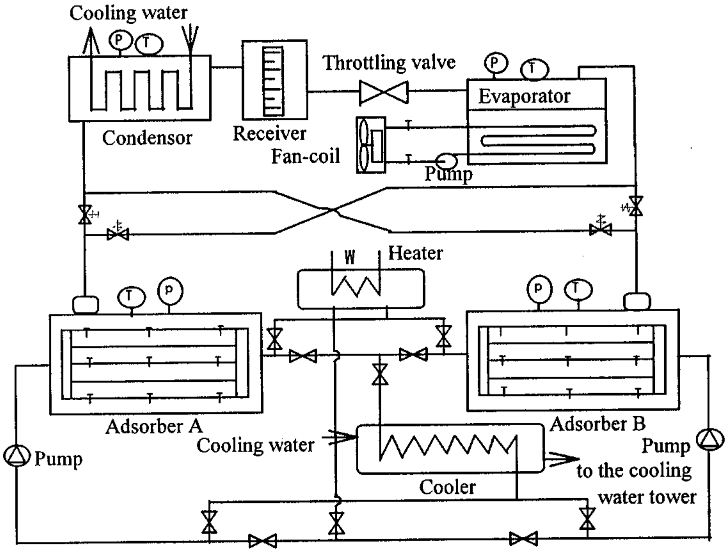


Figure 5. Schematic drawing of the whole adsorption heat pump system

Table 2. Performance parameters at different conditions

Maximum heating power (kW)	1. 25 kW	2. 25 kW	3. 12 kW
Heating source temp. (°C)	95	95	95
Desorption temp. (°C)	83	88	89
Adsorption temp. (°C)	52	44	45
Temp. of cooling water (°C)	27	28	27
Evaporating temp. (°C)	6·2	6·0	6·7
Refrigeration power (kW)	3·84	3·92	3·03
Power for desorption (kW h)	6·4	7·4	7·2
Cycle time (min)	30	40	60
COP	0·15	0·18	0·21

60 min, etc., have been tested, it has been found that longer cycle time yields a high coefficient of performance (COP) and a low specific power density (SPD). This indicates that the dynamic behaviour in adsorption systems are quite critical, we need both high COP values and high SPD, however they both are in contradiction. The satisfied cycle time for the system is between 30 and 40 min. Table 2 shows some experimental results regarding various cycle time and heating power.

In the results above, the COP is from 0·15 to 0·21, and the refrigeration power is from 3·0 to 3·9 kW. This COP value is far lower than the theoretical estimated value of about 0·6, which is mainly caused by the heat capacity of the adsorber mass and also the thermal fluid water (Teng *et al.*, 1997). Based on our testing results and heat balance analyses, we have estimated the potentials on cases if oil is used as thermal fluid, if double beds with heat recovery are applied, and if the mass of aluminum for the adsorber body is reduced to a comparatively low value. The estimated results can be shown in Table 3. The heat capacity ratio of the adsorber body mass plus thermal fluid to the adsorbent is 11·4 in the above system, our further improvement will ensure a level of 3·5, which will yield a COP value bigger than 0·5 and a SPD of about 150 W per kg-adsorbent.

Table 3. Air conditioning performance of the three experimental working conditions

Experiment	1.	2.	3.
Cycle time (min)	30	40	60
SPD ($W kg^{-1}$)	150	151	116
$COP_{sb, water}$	0·15	0·18	0·21
$COP_{sb, oil}$	0·194	0·220	0·264
$COP_{db, water}$	0·235	0·259	0·313
$COP_{db, oil}$	0·282	0·300	0·374
$COP_{db, improved}$	0·442	0·472	0·590

* sb = single bed, db = double beds; water/oil = water/oil as thermal fluid

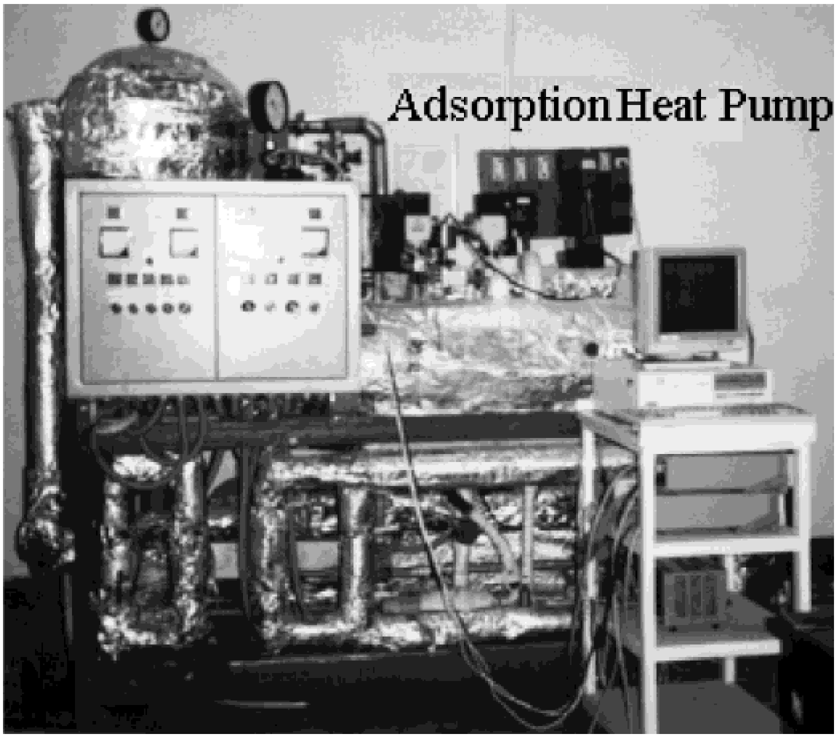


Figure 6. The outlook of the adsorption heat pump

4. DISCUSSIONS AND CONCLUSIONS

Two heat-regenerative adsorption systems, one for ice-making and one for air conditioning, have been developed and tested, in which activated carbon–methanol adsorption pair is used in both systems, with which spiral plate adsorber, plate-fin adsorber have been applied, respectively. The cycle time is short for the both systems, which means the good heat transfer in the two types of adsorbers.

It is clear that these adsorption systems are capable of a ice-making capability of more than 2·6 kg ice per kg-adsorbent per day, and a specific cooling power density for air conditioning of 150 W per kg-adsorbent. These adsorption systems can be applied for waste heat driven such as the waste heat from various engines (ice-making for fishing boat, air-conditioning for automobiles) and the solar power. The heat source needed for activated carbon–methanol system can be as low as 60°C.

The heat capacity ratio of the adsorber body plus thermal fluid to adsorbent is very critical to the COP value of an adsorption system (Teng *et al*., 1997), reasonable ratio is in the range of 3–5 to ensure high values for both COP and SPD. The expected COP for air conditioning with the single effect adsorption system heated by a source of 95 °C is greater than 0·5, which is now under development.

Time dependent adsorption and desorption should be investigated, because they have very significant influences on COP and SPD. The fundamentals of adsorption refrigeration and heat pump was established in steady-state cycle (Teng *et al*., 1997), which are not suitable for real adsorption systems. Dynamic analyses are necessary for the fundamentals study, which needs more research work.

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REFERENCES

Critoph, R. E. (1994). 'Forced convection enhancement of adsorption cycles', *Heat Recovery Systems & CHP*, **14**(4), 343–350.

Douss, N., Meuiner, F. E. and Sun, L. M. (1988). 'Predictive model and experimental results for a two-adsorber solid adsorption heat pump', *Ind. Engng. Chem. Res*., **27**(2), 310–316.

Meunier, F. and Douss, N. (1990). 'Performance of adsorption heat pumps: active carbon–methanol and zeolite–water pairs', *ASHRAE Trans*., 267–274.

Pons, M. and Guilleminot, J. J. (1986). 'Design of an experimental solar-powered solid-adsorption ice maker', *Trans. ASME J. Solar Energy Engng*. **108**, 332–337.

Shelton, S. V. and Wepfer, W. J. (1990). 'Solid–vapor heat pump technology', *IEA Heat Pump Conf*., Tokyo, pp. 525–535.

Teng, Y., Wang R. Z. and Wu J. Y. (1997). 'Study of the fundamentals of adsorption systems', *Appl. Thermal Engng*., **17**(4), 327–338.

Wang, R. Z., Teng, Y. and Wu J. Y. (1996). 'A continuous heat regenerative active carbon–methanol adsorption refrigerator using spiral plate heat exchanger as adsorbers', *Proc. Int. Ab-sorption Heat Pump Conf*., Vol. 1, pp. 587–594.

Wang, R. Z., Wu, J. Y., Xu, Y. X., Teng, Y. and Shi, W. (1998). 'Experiment on a continuous heat regenerative adsorption refrigerator using spiral plate heat exchanger as adsorbers', *Appl. Thermal Engng*., **18**(1), 13–23.