PERGAMON

Energy Conversion and Management 44 (2003) 1733–1743

ENERGY CONVERSION & MANAGEMENT

www.elsevier.com/locate/enconman

Adsorption cold storage system with zeolite–water working pair used for locomotive air conditioning

Y.Z. Lu, R.Z. Wang *, M. Zhang, S. Jiangzhou

Institute of Refrigeration and Cryogenics, School of Power and Energy Engineering, Shanghai Jiao Tong University, 1954 Hua Shang Road, Shanghai 200030, China

Received 12 October 2001; received in revised form 11 April 2002; accepted 10 July 2002

Abstract

Adsorption cold storage has lately attracted attention for its large storage capacity and zero cold energy loss during the storing process. Thermodynamic and experimental studies on the cold storage capacity and the cold discharging process, in which the adsorber is either air cooled or adiabatic, have been presented. An adsorption cold storage system with zeolite–water working pair has been developed, and some operating results are summarized. This system is used for providing air conditioning for the driver's cab of an internal combustion locomotive. Unlike a normal adsorption air conditioner, the system starts running with the adsorption process, during which the cold energy stored is discharged, and ends running with the generation process. The adsorbent temperature decreases during the cold storing period between two runs. The refrigeration power output for the whole running cycle is about 4.1 kW. It appears that such a system is quite energetically efficient and is comparatively suitable for providing discontinuous refrigeration capacity when powered by low grade thermal energy, such as industrial exhausted heat or solar energy.
© 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Adsorption; Cold storage; Exhaust heat; Locomotive

1. Introduction

Energy storage is very important in a variety of thermal engineering applications. In many cases, the energy supply does not always correspond with the demand. So, a lot of energy may as

* Corresponding author. Tel.: +86-21-6293-3250/3838; fax: +86-21-6293-2601/3250.
E-mail address: rzwang@mail.sjtu.edu.cn (R.Z. Wang).

0196-8904/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0196-8904(02)00169-3

Nomenclature

COP	coefficient of performance
c_p	specific heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
h_{fg}	latent heat of evaporation ($\mathrm{J\,kg^{-1}}$)
K	constant
m	mass (kg)
$\dot{m}$	mass flow rate ($\mathrm{kg\,s^{-1}}$)
n	constant
p	pressure (Pa)
P	refrigeration power (W)
q_{ad}	adsorption heat ($\mathrm{J\,kg^{-1}}$)
q_{out}	refrigeration capacity output for unit mass of adsorbent ($\mathrm{J\,kg^{-1}}$)
q_{st}	cold storage capacity for unit mass of adsorbent ($\mathrm{J\,kg^{-1}}$)
Q_{in}	thermal energy input (J)
Q_{out}	refrigeration capacity output (J)
Q_{st}	cold storage capacity (J)
t	time (s)
T	temperature (K)
T_0	ambient temperature (K)
T_a	adsorption temperature (K)
T_g	generation temperature (K)
x_0	maximum adsorption capacity ($\mathrm{kg\,kg^{-1}}$)
x_1	rich adsorption capacity at ambient temperature ($\mathrm{kg\,kg^{-1}}$)
x_2	rich adsorption capacity at end of cold discharge ($\mathrm{kg\,kg^{-1}}$)
x_3	poor adsorption capacity during cold storage ($\mathrm{kg\,kg^{-1}}$)
ε	cold discharge ratio

Subscripts

a	adsorbent
b	metal
bed	adsorbent bed
chil	chilled water
cond	condenser
ev	evaporator
f	heat transfer fluid
gas	exhaust gas
in	inlet or input
out	outlet or output
s	saturation
r	refrigerant

well be stored for later use when the energy supply is superfluous. Cold storage is especially concerned more and more because cooling applications now represent a large amount of energy consumption. In most conventional cooling systems, there are mainly two types of cold storage. The first one is sensible cold storage, in which the temperature of the storage material varies with the amount of energy stored. The other one is latent cold storage, which makes use of energy stored when a substance changes from one phase to another by melting. These two cold storages mentioned above are both low temperature cold storages, for the temperature of the cold storage tank is lower than the environment temperature. Accordingly, the cold energy loss in such a system must be considered during the storing period, which is disadvantageous for the system, especially when it is used for a long term storing period.

The working principle of adsorption cold storage involves reversible physical–chemical processes in which thermal energy is stored via adsorption. In this case, the cooling capacity can be preserved for a long term with no pollution and no cooling energy losses, and it is readily discharged when needed only by connecting the adsorbent bed to the evaporator. This method of cold storage can be used in a solid adsorption refrigeration system powered by exhaust heat or solar energy. Also, an adsorption cold storage system, after energy charging, can be moved to a place that cannot provide energy by itself to produce refrigeration power for cold preservation or short term air conditioning.

Extensive investigations on an adsorption heat pump or refrigeration have been conducted after the energy crisis in the 1970s. Simultaneously, interest in adsorption energy storage has also increased slightly. Early researches on adsorption energy storage were mainly about heat storage. An open cycle adsorption heat storage system using a zeolite–water pair was analyzed theoretically by Close and Pryor [1]. Parrish et al. [2] developed a heat pump adsorption spacecraft thermal storage device, which showed superior thermal storage characteristics when compared with other systems under typical use conditions. Also, the adsorption chiller, driven by exhaust heat, has been used to charge cold for an ice cold storage system during the night so as to be applied to the cogeneration system for facilities with no cold demand at night [3]. These years, adsorption energy storage, especially cold storage, has attracted more and more attention. The adsorption characteristics of a heat pump/energy store system using silica gel and water as a working pair were studied by Tahat [4]. A comparison between different sorption systems, such as absorption, adsorption and solid/gas reaction, was presented with relation to their storage capacity for cooling by Mugnier and Goetz [5]. However, there are still no reports on the engineering application of adsorption cold storage.

In this paper, thermodynamic analysis and experimental investigation of an adsorption cold storage system with a zeolite–water pair is presented. The application of the system for providing air conditioning for a locomotive cab is also studied.

2. Basic thermodynamic analysis of adsorption cold storage

The cold storage capacity of an adsorption cold storage system may be indicated by the difference of the adsorption capacities during the cold storing and discharging periods. The equilibrium adsorption capacity (the mass of refrigerant adsorbed by unit mass of adsorbent) normally can be expressed by the Dubinin–Astakhov equation [6]:

$$x = x_0 \exp\left[-K\left(\frac{T}{T_s} - 1\right)^n\right] \tag{1}$$

where T is the adsorbent temperature, T_s is the saturated temperature corresponding to the bed pressure p, x_0 is the maximal adsorption capacity and K and n are characteristic constants of adsorption, which have some relationship with the adsorbent material. Obviously, x varies between x_0 and zero at saturation and is a function of T and p.

The general principle of an adsorption cold storage cycle is given in the Clapeyron diagram shown in Fig. 1. The operating process of the system mainly consists of three periods: generation (A–B–C), cold store (C–E) and cold discharge (E–A). A normal adsorption refrigeration cycle (A–B–C–D–A) is also shown in the figure.

During the generation period, the adsorbent bed is heated with a rich adsorption capacity, x_2, until its pressure is equal to the pressure in the condenser, p_{cond}. Consequently, the refrigerant vapor is driven off and condensed in the condenser. After generation, the bed is cooled with a poor adsorption capacity, x_3, and the bed temperature decreases from the generation temperature, T_g, to the ambient temperature, T_0, during the cold storing period. The adsorption–evaporation process takes place when the cold is needed to be discharged. The refrigerant is drawn from the evaporator into the adsorbent bed at the saturated vapor pressure corresponding to the evaporation temperature, p_{ev}. The bed temperature may, at first, increase because of the latent heat of adsorption, which is on the contrary with the temperature decrease during an adsorption process for a traditional adsorption refrigeration system, and at last reach the adsorption temperature, T_a. It must be noticed that the adsorption process during this period, which is shown with a broken line (E–A) in Fig. 1, is strongly non-equilibrium.

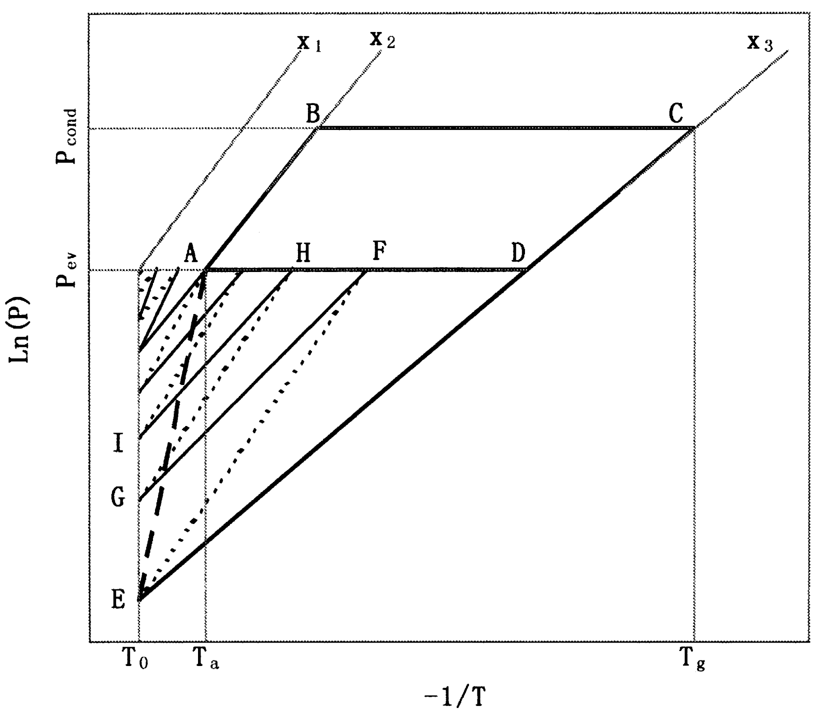

Fig. 1. Clapeyron diagram (ln(p) vs $-1/T$) of adsorption cold storage cycle.

The ideal cold storage capacity of an adsorption cold storage can be defined as the maximal potential refrigeration capacity caused by evaporation of the refrigerant, shown as following:

$$q_{st} = (x_1 - x_3)h_{fg} \tag{2}$$

where q_{st} is the cold storage capacity for unit mass of adsorbent, h_{fg} is the latent heat of evaporation of the refrigerant at T_{ev}, and x_1 is the rich adsorption capacity at the end of cold discharge when $T_a = T_0$.

The bed temperature at the end of the cold discharging period is normally greater than the ambient temperature. Therefore, the theoretical refrigeration capacity output, q_{out}, is less than q_{st}.

$$q_{out} = (x_2 - x_3)h_{fg} \tag{3}$$

Then, the cold discharge ratio is defined as follows:

$$\varepsilon = \frac{q_{out}}{q_{st}} = \frac{x_2 - x_3}{x_1 - x_3} \tag{4}$$

The cold storage capacity of an adsorption cold storage system can be discharged either by an air cooled process or by an adiabatic process. The former means cooling the adsorbent bed by ambient air in the process of cold discharge. Such a process will continue until the temperature of the bed is very close to that of the cooling fluid.

As to the process of adiabatic adsorption, which means that there is no heat transfer fluid passing through the adsorber, the latent heat of adsorption will be transferred into the sensible heat of the adsorbent bed and the metal materials of the adsorber. The energy equilibrium equation of the adsorber can be expressed as follows:

$$m_a q_{ad}\,dx = m_a(c_{p,a} + x c_{p,r})\,dT + m_b c_{p,b}\,dT \tag{5}$$

where m_a and m_b are the masses of adsorbent and the metal material, respectively, and q_{ad} is the adsorption heat for unit mass of refrigerant.

The cold storage system still has quite large cold capacity after the first adiabatic adsorption. When the bed temperature decreases again, the cold capacity of the system can be discharged once more. So, the adiabatic cold discharge can take place many times, shown as the processes E–F and G–H in Fig. 1.

3. Experimental setup

An adsorption cold storage/air conditioning system using zeolite and water as a working pair has been installed in an internal combustion engine locomotive for producing chilled water for air conditioning the driver's cab. The system is shown schematically in Fig. 2. The adsorbent bed is filled with 140 kg of 13X zeolite grains, and there are totally 185 kg of water filled in the adsorber and the evaporator, which acts not only as refrigerant but also as the coolant medium for the sensible heat cold storage providing cooling during the generation period. In addition, the total mass of the metal material of the adsorber is 250 kg.

This locomotive runs between Shanghai and Hangzhou, which are both located in the east of China. The running time is about 2 h, and there is an intermission of several hours between two runs.

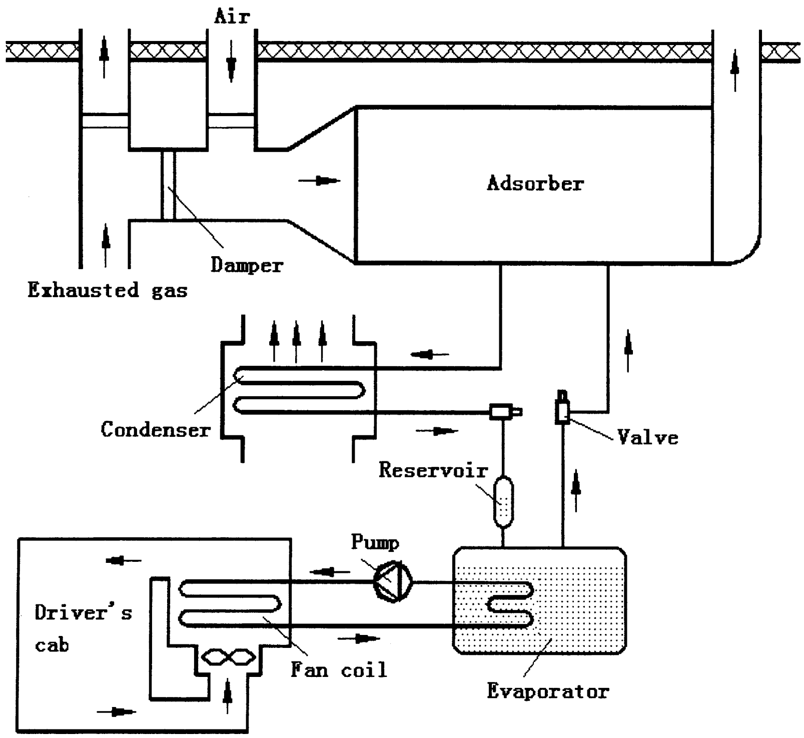

Fig. 2. Schematic of the experimental setup.

The operating test starts with cold discharge, that is, the valve between the adsorber and the evaporator is open at the start of the locomotive when the bed temperature is quite low. At the same time, the adsorber is cooled by ambient air. Because of the water vapor adsorption on the zeolite, the bed temperature increases rapidly, and the evaporator temperature decreases. Consequently, the pump, which circulates the chilled water running between the evaporator and the fan coil, is actuated when the evaporator temperature is low enough. Thus, the cold is discharged to the cab by the chilled water. During the generation period, the adsorbent bed is heated by the high temperature gas exhausted from the internal combustion engines. Subsequently, the refrigerant vapor is desorbed and condensed in the air cooled condenser. During this period, the refrigeration power output is realized by the sensible cold discharge of the water in the evaporator. The cold storing period starts when the locomotive stops running. Then, the adsorbent temperature is decreased slowly because of the natural heat dissipation to the ambient.

The temperature within the adsorber is measured at seven positions by thermocouples, while the temperatures of the water in the evaporator and in the condenser are, respectively, observed from several resistor thermometers. Besides the temperatures, the pressures in the adsorber, the condenser and the evaporator are also measured.

The temperatures of the heat exchanging fluid (exhaust gas, air and chilled water) are measured at the inlet and the outlet of the heat exchanger. The experimental refrigeration power output is calculated from the temperature difference of the inlet and outlet of the chilled water multiplied by its flow rate.

$$P_{\text{out}} = \dot{m}_{\text{chil}} c_{p,\text{chil}} (T_{\text{chil,in}} - T_{\text{chil,out}}) \tag{6}$$

Thus, the total refrigeration capacity output is

$$Q_{\text{out}} = \int P_{\text{out}}\,\mathrm{d}t \tag{7}$$

Similarly, the thermal energy input is calculated as

$$Q_{\text{in}} = \int \dot{m}_{\text{gas}} c_{p,\text{gas}} (T_{\text{gas,in}} - T_{\text{gas,out}})\,\mathrm{d}t \tag{8}$$

The mass flow rate of the chilled water, $\dot{m}_{\text{chil}}$, is measured by a flow meter, and it is a constant value of 0.29 kg/s, while the mass flow rate of the flue gas exhausted from the internal combustion engines, $\dot{m}_{\text{gas}}$, varies with running time, and its average value is about 1.0 kg/s.

The coefficient of performance (COP) of the air conditioning system is determined as

$$\text{COP} = Q_{\text{out}}/Q_{\text{in}} \tag{9}$$

4. Experimental results and discussions

4.1. Cold storage capacity

The behavior of the water adsorption on zeolite has been studied to find the factors that may determine the adsorption characteristic performance. The adsorption isobars of zeolite–water with different adsorbent temperatures under equilibrium conditions are presented in Fig. 3, in which the saturated temperatures corresponding to the bed pressures are 10, 34 and 45 °C respectively. From the experimental data, the simulated equilibrium adsorption capacity can be expressed as follows:

$$x = 0.261 \exp(-5.36(T/T_s - 1)^{1.73}) \tag{10}$$

From the above equation, the maximal cold storage capacity for unit mass of zeolite is calculated as 600 kJ for 1 kg of zeolite, when T_{bed} and T_{ev} are 30 and 5 °C, respectively. This value is

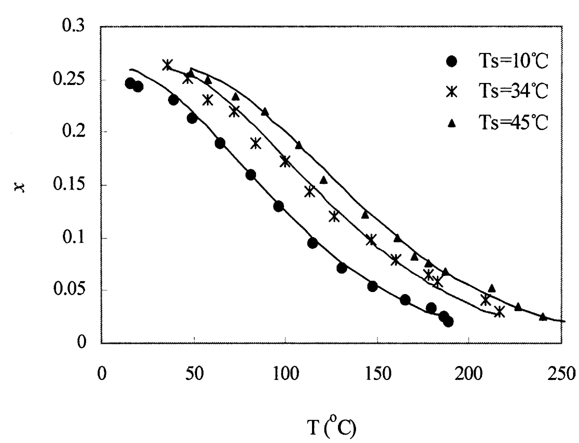

Fig. 3. Adsorption capacity isobars of zeolite–water working pair.

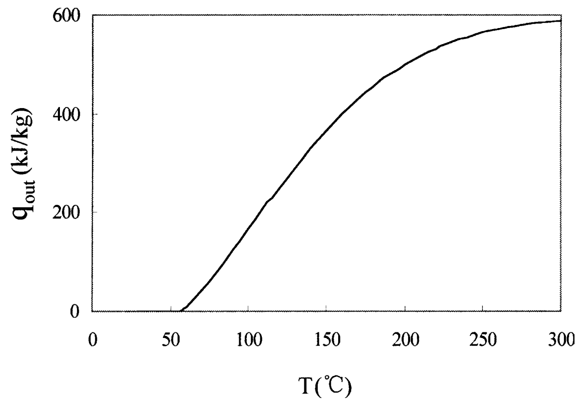

Fig. 4. Effect of generation temperature on cold storage capacity.

quite large when compared to other systems applied for cold storage. For example, it is about 4.2 kJ/kg when the water temperature changed 1 K for a sensible heat cold storage system using water. It is also much greater than that of the ice cold storage system with the same mass of 333 kJ/kg. As for the presented experimental system, the total maximal cold storage capacity is 84 MJ.

The experimental results show that the amount of water desorbed from the zeolite is increased with the increase of generation temperature. Thus, the cold storage capacity, as well as the adsorption capacity, varies with generation temperature, as presented in Fig. 4 where T_{ev} and T_0 are 5 and 30 °C, respectively.

4.2. Performance investigation of the system

The experiment with air cooled cold discharge was conducted when T_{bed} is 60 °C after a cold storage period of about 7 h. The variations of T_{bed}, T_{ev}, T_{chil}, and P_{out} with running time are shown in Figs. 5 and 6, respectively.

At the start of the cold discharge, T_{bed} increased rapidly because of the effect of adsorption and then decreased gradually. T_{ev} decreased from 30 to 20 °C in 5 min, and then, the cold was outputted

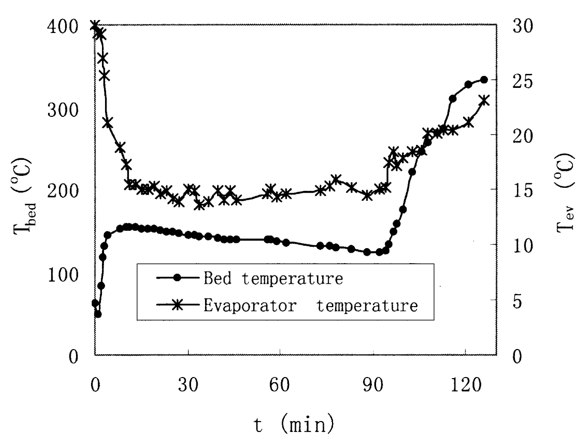

Fig. 5. Variation of adsorbent temperature and evaporator temperature.

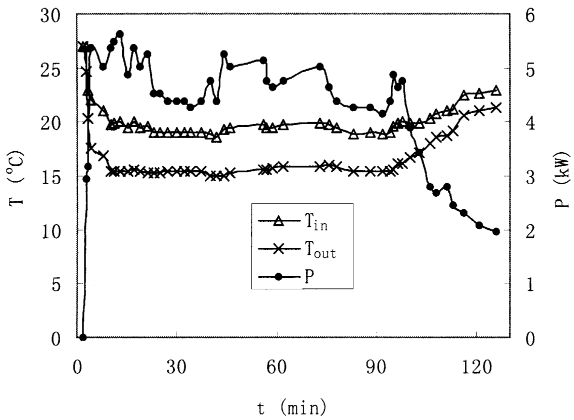

Fig. 6. Variation of the inlet and outlet temperature of the chilled water and the refrigeration power output.

to the cab by the chilled water. The refrigeration power was more than 4.2 kW during most of the cold discharging period, which lasted for about one and a half hours.

After the discharging period, the adsorbent bed was heated by the high temperature exhaust gas. The generation period lasted for 30 min during which the bed temperature reached to near 350 °C, while the condenser temperature was 60 °C. During the generation period, the air conditioning of the cab was realized by the sensible heat cold discharge of water in the evaporator. As a result, the evaporator temperature increased. However, the refrigeration power during the sensible cold discharge was less than that during the adsorption cold discharge.

During the test, the temperature of the air conditioned cab was kept at about 25 °C for most of the time, while the ambient temperature was about 33 °C. The average refrigeration power for the whole running cycle was calculated as 4.1 kW, and the cold discharge ratio was 0.35. The cycle COP of the air conditioning system was calculated as 0.25.

When the locomotive stopped running and stayed at the railway station, the cold storing period started, and the adsorbent bed continued to be cooled by the natural convection of the ambient air. Thus, T_{bed} approached the ambient temperature at the start of the next run, which is advantageous for the adsorption air conditioning system.

If the running time is changed, normally from 1.5 to 3 h, the cold discharging period may be also changed according to the cycle time, while the generation period varies from 15 to 30 min.

There are still some drawbacks for the system. Firstly, the small air flux cooling the adsorbent bed, whose average value is only about 0.5 kg/s, results in poor heat exchange between the air and the adsorbent bed. Therefore, the adsorption temperature at the end of cold discharge is as high as 120 °C, and so, the cold discharge ratio is considerably low. Secondly the mass transfer in the adsorbent bed is also not good. Enhancement of the heat and mass transfer of the adsorbent bed will be firstly regarded for further improvement on the system to get a higher refrigeration power or reduce the volume and mass of the adsorber.

4.3. Adiabatic cold discharge

Adiabatic cold discharge is helpful in an emergency when there is no head-on air to cool the adsorbent bed. Fig. 7 shows the simulated and experimental results of ε for the presented system

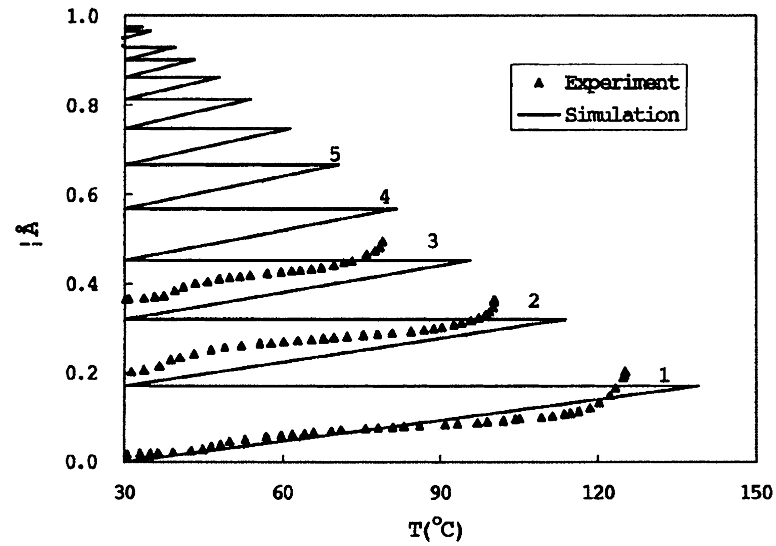

Fig. 7. Adsorbent temperature and cold discharge ratio during adiabatic cold discharge.

varying with T_{bed} during an adiabatic cold discharging period, when T_0 and T_{ev} are 30 and 5 °C, respectively. The numbers shown in the figure indicate the ordinal times in a series adiabatic adsorption.

This part of the experiments on adiabatic adsorption were conducted in our laboratory before the system was installed in the locomotive. After a whole day of cold storing, the adiabatic adsorption began by opening the valve between the adsorbent bed and the evaporator. The initial experimental cold storage ratio didn't start with zero because there was still a little water remaining in the adsorbent bed after the generation period. The experimental refrigeration capacity of the first cold discharge was obtained as 19.7 MJ when T_{bed} reached its maximum temperature of 125 °C. However, the simulated result of T_{bed} after cold discharge is 139 °C, while the cooling output is 14.3 MJ and the cold discharge ratio is 0.17. The main reason that the experimental T_{bed} could not reach as high as the simulated one is the heat dissipation from the bed to the environment.

After the first cold discharge, the bed temperature decreased slowly to the environmental temperature again during the next cold storing. Thus, the second time of cold discharge could be performed on the next day. The variations of T_{bed} and ε during the second and also the third cold discharge, shown in the figure, were similar to those of the first except that T_{bed} at the end of the cold discharging period and the variation of ε both decrease.

5. Conclusions

The following characteristics of the adsorption cold storage system can be concluded from the thermodynamic and experimental studies above mentioned:

1. The adsorbent–adsorbate combinations have large cold storage capacities. For the zeolite–water working pair, this value will be up to 600 kJ for 1 kg of zeolite.

2. Adsorption cold storage can make use of low grade thermal energy with no pollution and no cold energy losses.
3. The cold discharging process can be carried through when the adsorbent bed is air cooled or is adiabatic.

The application of the adsorption cold storage system with the zeolite–water working pair on the locomotive air conditioning can be considered to be successful. This system is simple and can be handled easily compared with other multi-bed adsorption systems. Also, the operating process of the system is in conformity with the running time of the locomotive. An average refrigeration power of about 4.1 kW is obtained, which is enough to make the driver's cab fairly comfortable. However, the heat and mass transfer of the adsorber needs to be improved to get better performance. Such an adsorption cold storage system appears to be competitive for providing refrigeration capacity at intervals in the field of low grade thermal energy utilization.

Acknowledgements

This work was sponsored by the State Key Fundamental Research Program of China (no. G2000026309), the Research Fund for the Doctoral Program of High Education under the Contract no. 2000024808 and also the Teaching and Research Award Program for Outstanding Young Teachers in High Education Institutions of MOE, China.

References

[1] Close DJ, Pryor TL. Behavior of adsorbent energy storage beds. Solar Energy 1976;18(4):287–92.
[2] Parrish CF, Scaringe RP, Pratt DM. Development of an innovative spacecraft thermal storage device. Proc Intersoc Energy Conv Eng Conf, IEEE 1991;4:279–84.
[3] Hisaki H, Kobayashi N, Yonezawa Y, Morikawa A. Development of ice-thermal storage system using an adsorption chiller. Proc Int Absorp Heat Pump Conf, ASME 1994:439–44.
[4] Tahat MA. Heat-pump/energy-store using silica gel and water as a working pair. Appl Energy 2001;69:19–27.
[5] Mugnier D, Goetz V. Energy storage comparison of sorption systems for cooling and refrigeration. Solar Energy 2001;71(1):47–55.
[6] Teng Y, Wang RZ, Wu JY. Study of the fundamentals of adsorption systems. Appl Therm Eng 1997;17(4):327–38.