RESEARCH ON A COMBINED CYCLE OF HEATING AND COOLING WITH SOLID ADSORPTION IMPLEMENTATION

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ABSTRACT

A combined cycle capable of heating and adsorption refrigeration is proposed, and the experimental prototype has been installed. The system consists of a heater, a water bath, an activated carbon-methanol adsorption bed and a ice box. This system has been tested with electric heating, and has been found that with 61 MJ heating, the 120 kg water in the bath can be heated up from 22 °C to 92 °C meanwhile 9 kg ice of -1.5 °C is made. The calculated COP_{system} is 0.0591 and COP_{cycle} is 0.41. After reconstruction to a real hybrid household water heater-refrigerator, when 55MJ heating is added to 120kg 21 °C water, and the condensing temperature is controlled at about 30 °C, the result is the 4kg water contained inside the methanol refrigerant evaporator was iced to -2 °C, the cooling capacity of the ice and the refrigerant in the evaporator will maintain the 100 liter cold box for about three days below 5 °C. The experiments show the potentials of the application of the solar powered hybrid water heater and refrigerator. Theoretical simulation has been done, which is in good agreement with experimental results. This research shows that the hybrid solar water heating and ice-making is reasonable, and the combined cycle of heating and cooling is meaningful for real applications of adsorption systems.

KEYWORDS

Solar energy, adsorption refrigeration, water heater, refrigerator, hybrid

INTRODUCTION

The expanding population and the crisis of energy have brought serious problems for the world environment. The electric driven vapor compression refrigeration system has been faced a challenge as CFCs and HCFCs are not suitable for sustainable development. The commonly substitutes of refrigerant R134a is also facing the problem of green house effect. Natural refrigerants such as water, ammonia, methanol and etc. will be welcome for the future refrigeration and air conditioning industries, however good use of energy should be ensured.

The use of waste heat and solar energy for refrigeration and air conditioning purposes has been accepted by people, various sorption systems have been developed and proved attractive[1-4] , but the real application is still limited. LiBr-water absorption systems for air conditioning has had big market in the last several years, specially in Japan, China and Korea. Regarding energy saving (heat, gas, oil, electricity) absorption systems are now facing the disadvantages as the electric driven central air conditioning chillers have reached COPs varying from 2.5 to 6, however the COP of available commercial double effect LiBr-water absorption chillers are usually in the range 1.1-1.25 if driven by heating.

Adsorption system is advantageous in small scale systems if compared with absorption system, the adsorption system could be operated with no-moving parts, and the rectifier or solution pump are not needed, the cost of it is also cheaper. But its COP is usually small than absorption system. For solar energy utilization, solid adsorption system is the well accepted system for refrigeration purposes, as the desorption temperature could be lower than 100 °C. The heating-desorption-condensation and cooling-adsorption -evaporation processes are well suited for solar energy.

Solar water heater is widely developed, various types of solar water heater such as plate type, evacuated tube type and heat pies type solar collectors are used to absorbe solar radiation. China has developed a good market for solar water heater in recent 5 years, the total sale of solar water heater has had a market of about 3 billion RMB Yuan (1 RMB Yuan accounts of 1/8 US$) each year, the total applied solar collector are 4.3 million m^2 in 1995, 12.53 million m^2 in 2000, the annual increase is now 2.5 million m^2. It is estimated that China has 5 million solar water heater installed in families in 2000.

The solar radiation heat source varies with seasons, the hot the climate, the strong the solar radiation, surely the more need for refrigeration. Adsorption refrigeration is a good way to utilize solar energy. This paper shows a combined cycle for solar heating and cooling, in which a hybrid system of solar water heater and an adsorption ice maker are incorporated together. This system is of great interests for solar refrigeration.

HYBRID SYSTEM OF SOLAR WATER HEATER AND ADSORPTION ICE MAKER

Various solar refrigerators using activated carbon-methanol adsorption refrigeration pair have been developed, mostly of plate type adsorber/collector [5-8] , the solar heating efficiency is of course limited due to the heat dissipation to the environment. Evacuated tube type solar collector has been developed to improve heating efficiency for solar water heater, but it will have problems if used as solar adsorber/collector, -the cooling of adsorber will be difficult. If heat pipe evacuated tube solar adsorber/collector is used, the heating efficiency to the adsorbent bed is high, however the cooling –adsorption –evaporation process will dissipate heat to the outside.

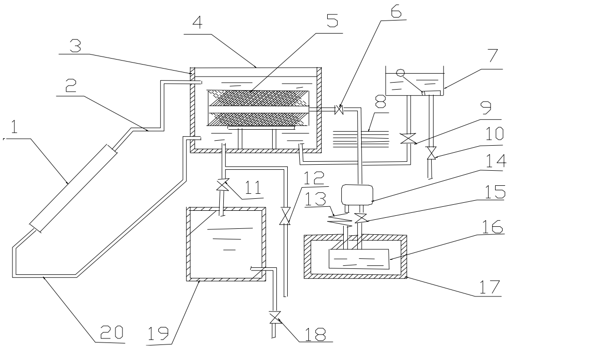

Fig.1:Schematics of a solar water heater and adsorption refrigerator. 1-Evacuated tube solar collector, 2,20-water pipe, 3-water tank, 4-cover plate of the tank, 5-adsorber, 6,9,10,11,12,15,18-valves, 7-water filling control system,8-condenser, 13-capillary tube,14-receiver, 16-evaportor, 17-ice box, 19-hot water reservoir.

If plate type solar collector/adsorber is used for refrigerator, it is needed for good heating during the day and good cooling during the night. The needs for heating and cooling are in contradiction, normally a compromise will be used to ensure cooling effectively in the night and meanwhile have small heat dissipation during the day[8].

In order to get high efficiency of solar heating, evacuated tube collector should be used, the good heating will be used to raise the temperature of water in the water tank, the water tank is well insulated by expanded foam. If the adsorber is immersed in the water tank, the adsorbent bed will be heated by water through heat conduction. Heating to the adsorber is thus well thermal insulated and the efficiency is high. During the night, if the hot water is drained out to another hot water reservoir or used out directly, city water will then be filled to the water tank, the cold water will then cool the adsorber very quickly, and cooling-adsorption-evaporation process can thereby initialized. During the cooling-adsorption-evaporation process, the sensible heat of the adsorber and the heat of adsorption will then be transferred to water in the tank. After the adsorption process, the water temperature in the water tank will be higher than the filled water temperature, this heat recovery process is important to save energy and the total solar energy efficiency is then increased.

A hybrid system of solar powered water heater and ice maker is constructed, which is just a combination of solar water heater and solar adsorption ice maker, shown as Fig.1.

The hot water is expected to be higher than 80 ^{o}C for the adsorption ice maker to work properly, this will ensure enough desorption of methanol from the adsorbent activated carbon. Due to the use of water tank and the adsorber is immersed into water, the adsorbent temperature is usually less than 100^{o}C, which makes methanol chemical stable.

Adsorber is designed as a group of tubes with a diameter of $\varnothing 50mm$, each tube is embedded with activated carbon, and the center of the bed is incorporated with a $\varnothing 10mm$ channel for mass transfer purpose. The total 30 tubes with a length of 800mm have been filled with 22kg activated carbon.

COMBINED CYCLE OF SOLAR WATER HEATING AND ADSORPTION REFRIGERATION

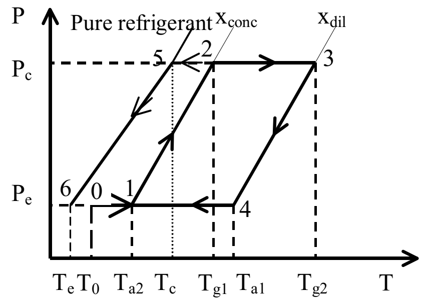

Fig.2: p-T-x diagram for an ideal combined heating and refrigeration system with heat recovery.

Based upon the concept shown as Fig.1, the operation of the hybrid combined cycle can be demonstrated as Fig.2, in which the heat recovery and ideal operation of refrigerator are shown in the p-T-x diagram.In Fig.2 the point "0" represents the filled water temperature, 0-1 represents the temperature increase of the water bath due to the heat recovery, 1-2-3-4-1 represents the ideal adsorption refrigeration cycle.

The useful heat from the collector Q_u, will contribute both to the heating of the water in the tank and to the heating of the adsorber which will cause the desorption of refrigerant from the adsorbent bed. The energy equation can be written as

$$Q_u = \int_{T_{a2}}^{T_{g2}} M_{water} C_{water} dT + \int_{T_{a2}}^{T_{g2}} (M_m C_{pm} + M_a C_{pa}) dT + \int_{T_{a2}}^{T_{g1}} x_{conc} M_a C_{pl} dT + \int_{T_{g1}}^{T_{g2}} h_d M_a dx + \int_{T_{g1}}^{T_{g2}} x(T, p_c) M_a C_{pl} dT \quad (1)$$

In which the first term represents the heat added to the water bath in the tank, the second term is the sensible heat of the metallic tank and adsorbent mass. Item 3 is the sensible heat of refrigerant liquid in the adsorbent before desorption, item 4 is the heat of desorption, item 5 is the sensible heat of refrigerant remained in adsorbent bed. In eqn.(1), M_{water} -mass of water, C_{water} -specific heat of water, M_m -mass of adsorber, C_{pm} -specific heat of adsorber, M_a -mass of adsorbent, C_{pa} -specific heat of adsorbent, C_{pl} -specific heat of refrigerant in the adsorbed state. Heat of desorption can be described by

$$H_d = \int_{T_{g1}}^{T_{g2}} h_d M_a dx = \int_{T_{g1}}^{T_{g2}} h_d M_a \frac{dx}{dT} dT \quad (2)$$

here h_d is the heat of adsorption, which is a function of x.

For the adsorption working pair, the adsorption equation of activated carbon - methanol can be described by equation[9]

$$x = x_0 \exp[-k(\frac{T}{T_s} - 1)^n] \quad (3)$$

where x is the adsorption capacity, k and n are the characteristic parameters of adsorption refrigeration pair, x_0 is the adsorption capacity at T=T_s and P=P_s (where T_s is the saturation temperature at pressure P_s),T is the adsorption temperature. Typical parameter values for the activated carbon-methanol pair are: x_0=0.284, k=10.21, n=1.39, T_s=288.3 K, where Shanghai "YK" (coconut shell type activated carbon) is used. h_d can be calculated from Clausius-Clapeyron equation, where $T_s = T_c$ (condensing temperature):

$$h_d = RA\frac{T}{T_c} \quad (4)$$

here R is the gas constant and A is the constant of Clausius-Clapeyron equation.

In the evening, the hot water in the tank is drained into another storage tank or is used directly. Cold water is then filled into the tank to cool the adsorber. The sensible heat of adsorber and the heat of adsorption will cause the filled water rises its temperature for several degrees, thus this energy will not be lost. The adsorption temperature T_{a2} is determined by the energy balance between the filled cold water and the adsorber to be cooled.

The sensible heat for cooling the adsorber bed from T_{g2} to T_{a2} is

$$Q_c = \int_{T_{a2}}^{T_{g2}} (M_m C_{pm} + M_a C_{pa}) dT + \int_{T_{a1}}^{T_{g2}} x_{dil} M_a C_{pl} dT + \int_{T_{a2}}^{T_{a1}} h_a M_a dx + \int_{T_{a2}}^{T_{a1}} x M_a C_{pl} dT \quad (5)$$

where item 1 is the sensible heat of adsorber mass and adsorbent, item 2 is the sensible heat of refrigerant in adsorbent bed, item 3 is the heat of adsorption, which can be calculated as

$$H_a = \int_{T_{a2}}^{T_{a1}} h_a M_a dx = \int_{T_{a2}}^{T_{a1}} h_a M_a \frac{dx}{dT} dT \quad (6)$$

item 4 is the sensible heat of adsorbent during adsorption process. The sensible heat for cooling is transferred to the filled cold water in the tank, this may cause the temperature increase for several degrees of the water in the tank.

If the filled water has a temperature T_0, then the water temperature after adsorption is

$$T_{a2} = T_0 + \frac{Q_c}{M_{water} \times C_{pwater}} \quad (7)$$

which is also the adsorption temperature for the refrigerator.

The desorbed refrigerant is condensed in the condenser and flows into the evaporator. When the adsorbent bed pressure is lower than evaporation pressure, the refrigerant liquid in the evaporator will evaporate which causes the refrigeration effect. The refrigeration quantity is

$$Q_{ref} = \Delta x M_a L_e \quad (8)$$

$$\Delta x = x_{conc} - x_{dil} \quad (9)$$

where L_e is the latent heat of vaporization, x_{conc} is the adsorbent capacity before desorption and x_{dil} is the adsorption capacity after desorption•

Some of the cooling quantity will be consumed to cool the refrigerant liquid from condensing temperature T_c to evaporation temperature T_e

$$Q_{cc} = M_a \Delta x C_{pl}(T_c - T_e) \quad (10)$$

Refrigeration Cycle COP can be written as

$$COP_{cycle} = \frac{Q_{ref} - Q_{cc}}{Q_g} \quad (11)$$

where Q_g is the heat for the regeneration of the adsorption bed, which is shown as

$$Q_g = Q_u - Q_{water} = \int_{T_{a2}}^{T_{g2}} (M_m C_{pm} + M_a C_{pa}) dT + \int_{T_{a2}}^{T_{g1}} x_{conc} M_a C_{pl} dT + \int_{T_{g1}}^{T_{g2}} h_d M_a dx + \int_{T_{g1}}^{T_{g2}} x M_a C_{pl} dT \quad (12)$$

$Q_{water} = \int_{T_{a2}}^{T_{g2}} M_{water} C_{water} dT$ is the sensible heat to heat the water in the tank, here the sensible heat to heat the tank is neglected.

In a normal solar powered adsorption ice-maker, the collector is in the same unit of adsorber, Q_{water} is zero, Q_u is the whole contribution of heating to the adsorber. In this case the energy Q_c must be taken away in the evening and the whole night to furnish the refrigeration effect. Cooling by normal convection is difficult to release Q_c .

The hybrid system has two useful output, one is refrigeration, its solar efficiency is

$$COP_{solar} = \frac{Q_{ref} - Q_{cc}}{\int G(t)dt} \quad (13)$$

another is heating the water in the tank, its solar efficiency is

$$\eta_{solar} = \frac{Q_{water}}{\int G(t)dt} \quad (14)$$

where G(t) is the solar flux density, $\int G(t)dt$ is the total solar energy during the whole day.

For the refrigeration cycle itself, the efficiency of the cycle could be estimated as

$$COP_{cycle} = \frac{Q_{ref} - Q_{cc}}{Q_h + Q_g} \quad (15)$$

PERFORMANCE SIMULATION

A hybrid system of solar water heater and refrigerator has been imaged. The system parameters and the parameters for simulation are listed in table 1. In the concept design, a stainless steel tube type adsorber with a diameter of 230 mm had been tried, and activated carbon was filled, the mass of adsorber and activated carbon are 5 kg and 28 kg respectively [10].

Table 1: Simulation parameters of the hybrid solar water heater and ice maker

Materials	Mass (kg)	Specific heat (J/kg·K)
Adsorbent carbon	$M_a = 28$	$C_{pa} = 900$
Adsorber stainless steel	$M_m = 5$	$C_{pm} = 902$
Water in the tank	$M_{water} = 50$	$C_{pwater} = 4180$
Methanol: $C_{pl} = 750(J/kg \cdot K)$, $x_0 = 0.284$ kg/kg, k=12.21, n=1.39, $T_s = 288.3$ K, A=4413, Le=1102 (kJ/kg).		

The solar heat flux density is taken from the solar source in Shanghai, and the total radiant energy to the collector is assumed to be $\int G(t)dt$=20MJ/m^2 per day, the efficiency of solar collector is 46% (depending on the product). A solar collector of vacuum tube heat pipe type is selected (efficient area for about 2m^2), its performance parameters are based on the product performances. Table 2 shows the simulated results for the typical climate of four seasons in Shanghai in a year.

In the simulation, a fixed solar heat flux density of 20MJ/m^2 per day has been assumed, this value will be changed for the real four seasons. However the simulation results show that about 6-10 ^{o}C temperature increase in water bath will be generated by the sensible heat and adsorption heat in the adsorbent bed, which will spare the energy for solar heating. It is also found that the refrigeration effect is strongly influenced by condensing temperature, it would be suggested to put the condenser partly or fully in a water bath to decrease the condensing temperature specially in summer time.

Table 2: Simulated results of the hybrid system for the whole year.

Seasons	Jan.- March	April - June	July - Sept.	Oct. - Dec.
Filled water temp.To (OC)	10	15	25	10
Condensing temp.Tc (oC)	20	25	35	15
Evaporation temp.Te (oC)	-10	-10	-10	-10
Adsorption temp.Ta2 (oC)	19.6	23.7	31	19.5
Generation temp.Tg2 (oC)	86.6	93.1	100	84.9
COPcycle	0.48	0.44	0.32	0.51
COPsolar	0.042	0.044	0.038	0.046
•solar	0.372	0.361	0.341	0.370
Ice made per day (kg)	7.9	6.3	3.05	8.7

EXPERIMENTAL RESEARCH

An electric heater is used to simulate solar heating. For a solar collector, an average accepted radiation power of 500 W/m^2 is assumed, thus a 1500 W electric heater can simulate a 3 m^2 evacuated solar collector. The performances of a hybrid system of electric water heater and adsorption refrigerator are

$$COP_{system} = \frac{Q_{ref} - Q_{cc}}{Q_u} \quad (16)$$

$$\eta = \frac{Q_{water}}{Q_u} \quad (17)$$

The experimental system has filled 120 kg water, however a market system will be good for 60 kg hot water output with a refrigeration capacity of about 5 kg ice per day. Table 3 shows some experimental results, where COP$_{60}$ represents the system COP when the hot water output is 60 kg. COP$_{60}$ is calculated based upon the experimental data by the definition as

$$COP_{system} = \frac{Q_{ref} - Q_{cc}}{Q_u - Q_{60}} \quad (18)$$

where Q_{60} is the heat of the subtracted 60kg water.

Fig.3: Hybrid system of water heater and refrigerator.

It should be indicated that the hybrid system of solar water heater and ice maker has been simulated with an electric water heater and refrigerator, which can meet the demand of family use. Fig.3 shows the new system with the combined cycles. The water heater incorporated with adsorber is as before, but here an ice box has been replaced by a refrigerator box. The measurement would not focus on heating and ice making, but on heating and cold storage.

In order to ensure good condensing effect, the condenser has been partly immersed into a water bath, which dissipate heat to its surroundings by natural convection. The evaporator has been changed from ice making device into an ice storage evaporator, seven closed stainless steel tubes (Φ50×410) filled with water were installed into a box-like evaporator. The total 4 kg water in the tubes is used for ice-storage, which is directly immersed into the methanol bath in the evaporator. The refrigeration will cause the temperature of methanol in the evaporator to drop down, which causes a refrigeration effect to the refrigerator box and meanwhile water-ice transformation in the evaporator could be also initialized.

For the measurement, there are 6 platinum resistor temperature sensors, shown as Fig.4, distributed in a 450×380×580mm refrigerator box, about 100 liter. Sensor 1 is mounted on the evaporator surface, sensors 2 and 3 are located at 90mm distance down to the evaporating surface, sensors 4 and 5 are at a distance of 250 mm to the evaporating surface, while sensor 6 is at the bottom of refrigerator box.

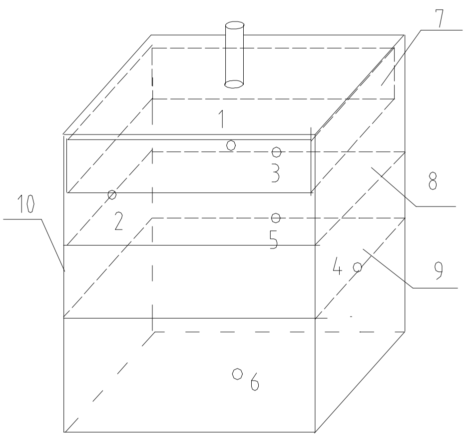

Fig.4: Arrangement of temperature sensors.1-6 -Pt100,7-evaporator, 8-support plate 1, 9-support plate 2, 10-refrigerator box.

Typical runs are: 120kg water was filled to the water tank with a temperature of 20 °C • condensing temperature 30 °C (which is achieved by part of the condenser immersed in a water tank for good cooling) , the electric heat input were 55MJ,50MJ and 40MJ respectively. Figs.5-7 show the experimental result for 55 MJ heat input. It is shown in Fig.5 that after 5 hr heating, there are a temperature drop down, which represent the start of desorption (desorption valve open). The desorption process needs heat input, if there is not enough heat input, then the adsorbent bed temperature drops down.

After 10 hr heating, the heating-desorption stopped, and the hot water is drained out, then city water is filled, the temperature of water bath and also adsorbent bed reduces rapidly, after the adsorbent bed pressure is lower than evaporating pressure, then adsorption process could be started. At 15 hr operation, the beginning of adsorption may causes rapid temperature rise due to the strong adsorption heat release.

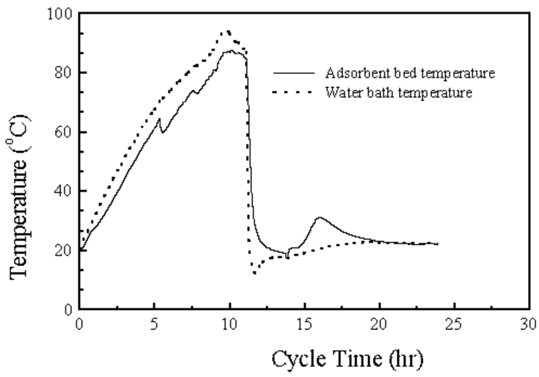

Fig.5: The adsorbent temperature and water bath temperature versus cycle time.

Fig.6 has shown the changes of temperatures in the refrigerator box when subjected one heating/refrigeration combined cycle. Sensor 1 shows the temperature of the evaporator surface, after adsorption started, this temperature goes down rapidly to –1.5 °C, and then rise up to –0.1 °C. In the following 4 hours, this temperature is kept in the range of 0—1.0 °C, this process is water-ice transformation process. When the 4 kg water inside the tube in the evaporator is iced, the temperature of sensor 1 still goes down till –2 °C. At 24hr of operation, the heating/refrigeration operation is stopped, the temperature variations in the refrigerator box is then observed. Typical example is for sensor 1, the temperature rises up and stabilized at about 0 °C, the refrigeration box will be kept cold depending on the 4kg ice in the evaporator.It is seen that during 15hr-70 hr period the cold box temperatures (sensors 1-6) are maintained below 5 °C, which proves that this refrigerator box is suitable for cold storage, one operation of heating and refrigeration cycle will guarantee for at least 55 hours for food storage.

Table 3 Hybrid system performance of heating and ice-making

Experiment date	Heating Energy(MJ)	Hot water		Ice		COP_{60}	COP_{cycle}	COP_{system}	•
		°C	kg	°C	kg				
April 10-11, 1999	61	92	120	-1.5	9.0	0.129	0.41	0.0591	0.575
April 15-16,1999	44.5	81	120	-1.2	6.0	0.113	0.386	0.0548	0.665
April 20-21, 1999	39.4	72	120	-1.2	4.5	0.095	0.37	0.0475	0.635

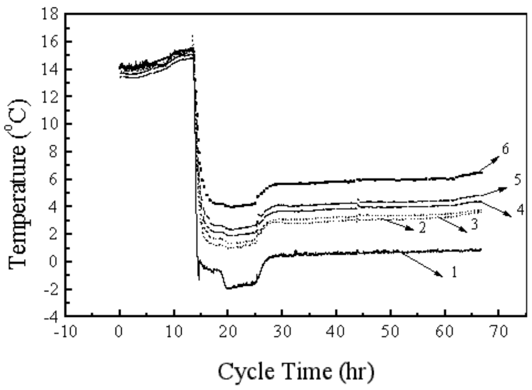

Fig.6: The temperatures in the refrigerator box varies with time subjected one heating/refrigeration cycle

Fig.7 shows the recorded cycle in a p-T-x diagram corresponding to a 55MJ heat input with a filled water temperature T_0=20 °C. The energy recovery by the water bath is well shown, the adsorption temperature T_{a2} reaches 27.3 °C due to the sensible and adsorption heat recovery, the recovered heat is about 3.7 MJ, which is 6.7% of the total heat input. The recorded data are well agreed with an ideal p-T-x diagram in which the cycle is consisted of two isotersis (heating and cooling) and two isobars (desorption at condensing pressure and adsorption at evaporation pressure) .

Fig.8 shows the cooling process when the refrigerator box has a 250 ml water cooling load, where the water container is located at the position of the plate 4 and 5 shown as Fig.4. After 2 hours cooling, the water temperature drops down from 18 °C to 6 °C, after 6 hours the water temperature is very close to the temperatures of sensors 4 and 5.

The experimental results have shown that for the case of 55 MJ and 50 MJ heat input, the lowest temperature of the evaporator surface is about –2°C, the 4 kg water in the evaporator is cooled by the methanol and iced completely. One such operation will yield a 100 liter cold box for 4 °C for more than 55 hours.

For the 40 MJ heat input, refrigeration effect is obvious however the 4kg water can not be fully iced. It is proved that it is still possible to keep the 100 liter cold box with a temperature below 4 °C for more than 24 hours. For the comparison of the above three experimental results, 50MJ heat input is more suitable to achieve good performance of heating and cooling.

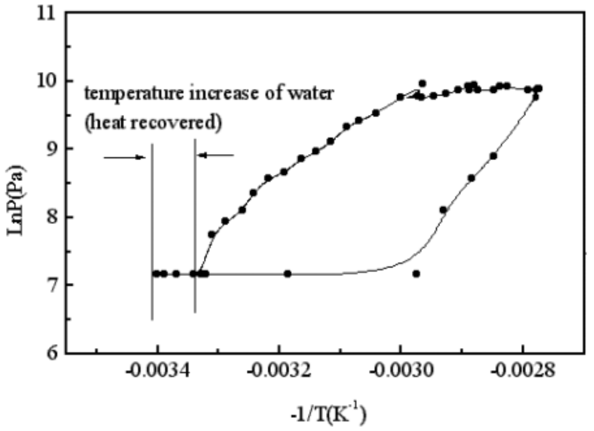

Fig.7: p-T-x diagram for the adsorption refrigeration cycle, in which the sensible heat and heat of adsorption are recovered by the water bath. (Heat input 55MJ).

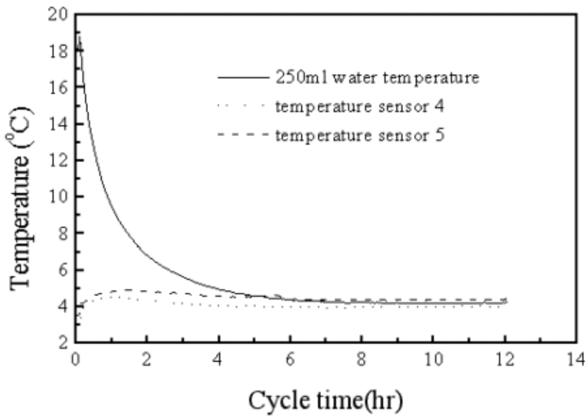

Fig.8: cooling load test of the refrigerator.

(a) (b)

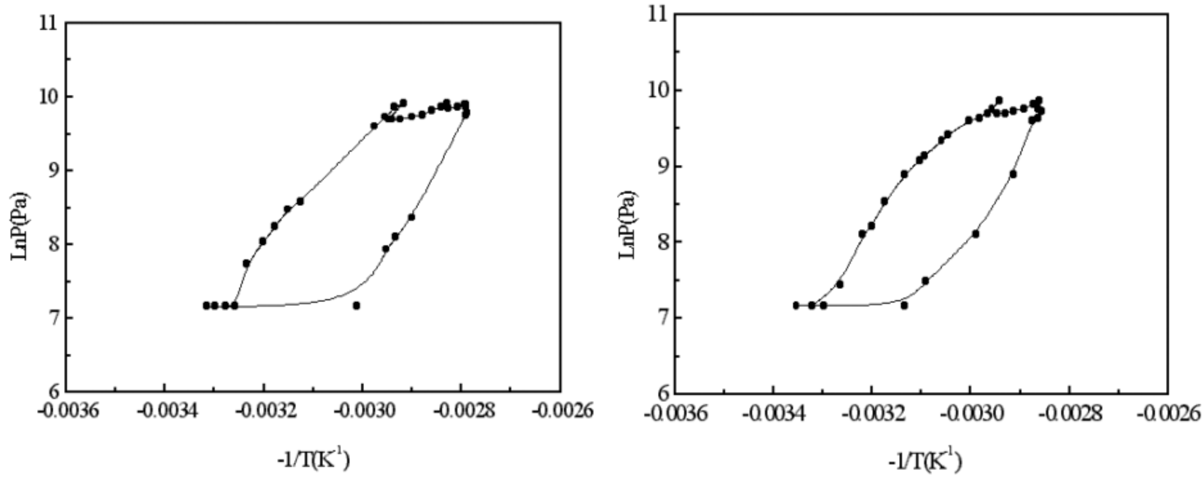

Fig.9: p-T-x diagram for the adsorption refrigeration cycle, in which the sensible heat and heat of adsorption are recovered by the water bath. (a): Heat input 50MJ, (b): Heat input 40 MJ.

DISCUSSIONS AND CONCLUSIONS

Based upon the proposed new idea of the combined cycle of heating and adsorption refrigeration, a hybrid solar powered water heater and refrigerator has been constructed and tested. This work shows

(1) In application: solar collector for water heater and solar collector for adsorption refrigeration can be unified as one solar collector for both water heating and adsorption refrigeration. One solar collector can be used for two purposes, which is reasonable for family use as both heating and refrigeration output are available.

(2) In construction: solar water heater and adsorption refrigerator are connected only with one tube for refrigerant flow, the adsorber is immersed into the water tank. In this case high efficiency solar collectors such as evacuated tube type and evacuated tube with heat pipe type can be used. The hybrid concept has solved the problem for good heating and good cooling to the adsorber.

(3) In energy efficiency: the hybrid system has had good use of solar energy, the heat recovery of sensible heat and adsorption heat is obvious, which is used again to heat water bath in the water tank.

(4) Such hybrid system with combined cycle of heating and refrigeration is very suitable for peak-shaving electric water heater in connection with adsorption refrigeration.

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Nomenclature

A	constant of Clausius-Clapeyron equation
C_{pa}	specific heat of adsorbent ($kJ/kg\cdot K$)
C_{pl}	specific heat of refrigerant liquid (k $J/kg\cdot K$)
C_{pm}	specific heat of metallic adsorber (k $J/kg\cdot K$)
C_{pwater}	specific heat of water (k $J/kg\cdot K$)
COP	refrigeration COP
COP_{cycle}	refrigeration cycle COP
COP_{solar}	solar power refrigeration COP
G(t)	Solar heat flux density (W/m^2)
h_a	heat of adsorption (k J/kg)
H_a	Integrated heat of adsorption (kJ)
h_d	heat of desorption (k J/kg)
H_d	integrated heat of desorption (kJ)
k	Characteristic parameter of adsorption pair
L_e	latent heat of evaporation of refrigerant (k J/kg)
M_a	mass of adsorbent (kg)
M_m	mass of metallic adsorber (kg)
M_{water}	mass of water in the tank (kg)
n	Characteristic parameter of adsorption pair
Q_c	heat to cool down the adsorber and adsorbent bed (kJ)
Q_{cc}	cooling consumed to cool down refrigerant from condensing temperature to evaporation temperature (kJ)
Q_{ref}	Refrigeration effect (kJ)
Q_u	heat transferred to the water tank (kJ)
T	temperature (^oC)
T_a	environmental temperature (^oC)
T_{a1}	temperature to start adsorption (^oC)
T_{a2}	adsorption temperature (^oC)

T_c condensing temperature (°C)

T_e evaporation temperature (°C)

T_{g1} temperature to start desorption(°C)

T_{g2} desorption temperature (°C)

T_s saturated temperature (°C)

T_0 filled water temperature (°C)

x adsorption capacity (kg-refrigerant/kg-adsorbent)

x_{dil} adsorption capacity at desorbed state (kg/kg)

x_{conc} adsorption capacity at adsorbed state (kg/kg)

x_0 adsorption capacity at a saturated pressure p_s corresponding to T_s (kg/kg)

η_{solar} solar heating efficiency

Δx adsorption capacity difference between adsorption phase and desorption phase $\Delta x = x_{conc} - x_{dil}$ (kg/kg)