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AN ENERGY EFFICIENT HYBRID SYSTEM OF SOLAR POWERED WATER HEATER AND ADSORPTION ICE MAKER

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Abstract—A new hybrid system of solar powered water heater and adsorption ice maker has been proposed. The working principle of the combined cycles of solar refrigeration and heating is described, theoretical simulation to the thermodynamic processes has been made. Experiments have been performed in a developed prototype hybrid system; it is verified that the hybrid system is capable of heating 60 kg water to about 90°C as well as producing ice at 10 kg per day with a 2-m^2 solar collector. © 2000 Elsevier Science Ltd. All rights reserved.

1. INTRODUCTION

The ecological problems and energy crisis in the world have induced scientists to develop sustainable energy utilization systems, in which solar energy is attractive. Various solar water heaters, such as plate type, vacuum tube type, heat pipe vacuum tube type etc., have been commercialized with the expanding market. In China, solar water heater has been marketed for about 1 billion Yuan per year, and it is still being developed. Solar powered ice-makers or refrigerators have been reported by a lot of researchers, in which both absorption or adsorption systems have been demonstrated (Iloeje, 1985; Pons and Guilleminot, 1986; Pons, 1987; Hajji *et al*., 1991), however a potential market seems to be necessary for further research and development.

In recent years, we have paid a lot of attention to adsorption refrigeration systems (both for ice-making and heat pump), and good experimental results have been obtained with activated carbon–methanol working pairs. With a heat source of about 90–100°C, we have achieved a specific cooling power of 2.6 kg ice/day per kg-adsorbent for ice-making (Wang *et al*., 1998a), and 150 W/kg-adsorbent for air-conditioning (Wang *et al*., 1998b). More work regarding activated carbon fiber–methanol pairs for ice-making is on the way, in which 5 kg-ice/day per kg adsorbent will be expected (Wang *et al*., 1997). Solar ice making is attractive by an adsorption system, however it needs both good heat collecting and heat release for the adsorber, which seems to be a contradiction. By the way, heat release means energy losses.

A hybrid system of solar powered water heater and ice maker has been suggested and developed by the authors, the idea is simple but effective! The adsorber of the adsorption ice-maker is put into a water bath which is powered directly by vacuum solar collector. No thermal insulation or enhanced convection are needed for the adsorber, it is just immersed into the water bath of a solar powered water heater, which guarantees both good heating or cooling of the adsorber. With a solar collector of a group of heat pipe vacuum tubes, and proper design of the system, it is possible to reach a bath temperature of up to 80–90°C after 1 day solar collecting, which is suitable as a heat source for the activated carbon–methanol adsorption refrigerator. The hot water will be taken away in the evening (be drained to another insulated water tank or used for taking showers for the whole family), and cold water will be filled in. This cools the adsorption bed and induces adsorption, and the refrigeration process happens almost the whole night. A similar hybrid system for heating and cooling has been developed by Zeo-Tech (Schwarz *et al*., 1997) in Munich, they used zeolite as adsorbent and water as refrigerant, the sensible heat of the adsorbent bed and the heat of adsorption were used to heat

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water, while cooling by adsorption–evaporation was used to keep cold in a cold box.

This solar energy system is a good combination of solar heating and solar cooling, it is estimated that with a 2-m^2 solar collector, 50 kg 84–100°C hot water can be made during a sunshine day, meanwhile 3.0–8.7 kg ice will be also produced in the night. The system will yield a solar refrigeration COP of about 0.04 and heating efficiency η of about 0.35–0.38. The above hybrid combined cycle has been well verified by experiment in a prototype system.

2. WORKING PRINCIPLE

The schematic design of a hybrid solar powered water heater and refrigerator is shown in Fig. 1. The system consists of a solar collector, water tank, adsorber/generator, condenser, evaporator, receiver and ice box and so on. Fig. 2 shows the configured system.

The working principle is just a combination of a solar water heater and adsorption refrigeration. Heating of the water tank is started in the morning through vacuum tube type solar collector. With the increase of the water temperature, the temperature in the adsorbent bed rises. In an ideal process, the adsorbent temperature could be very close to the water temperature in the tank. When the temperature in the adsorbent rises up to a temperature (T_{g1}) which causes the vapor pressure of the desorbed refrigerant up to the condensing pressure (P_c), desorption at constant pressure is initiated, the desorbed vapor is condensed in the condenser and collected in the receiver. This liquid flows to the evaporator via a flow rate regulating valve. The temperature of the water

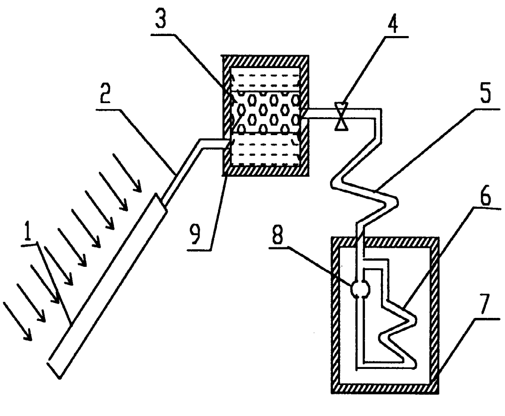

Fig. 1. Schematic of the solar water heater and refrigerator. (1) Solar collector; (2) water pipe; (3) adsorber; (4) valve; (5) condensor; (6) evaporator; (7) refrigerator (with cold storage); (8) receiver; (9) hot water container.

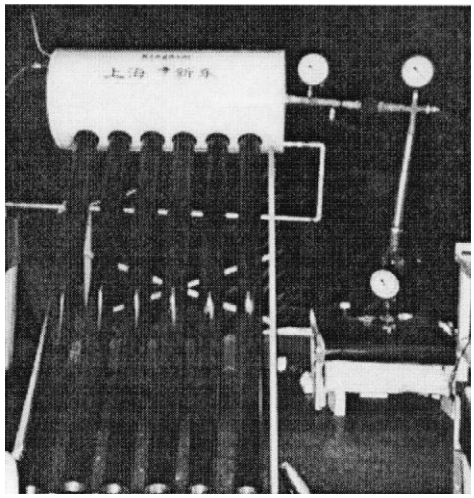

Fig. 2. The configured hybrid system of solar powered water heater and adsorption ice-maker.

and the adsorbent bed continues rising due to solar heating, a maximum temperature (T_{g2}) for 80–100°C could be achieved at the end of the process. The high temperature water is used in the evening for the family, also the hot water in the tank could be drained out and moved into another tank at home, thus hot water can be used very flexibly.

With the refilling of the water tank with cold water, the temperature of the adsorbent bed is reduced rapidly ($T_{g2} \rightarrow T_{a1}$), and the pressure in the adsorber drops to a value below evaporation pressure (P_e). Evaporation could happen if the connecting valve is open, and ice will be made in the refrigeration box. The cooling of the adsorber and the rejection of adsorption heat may cause the temperature of cold water in the tank to rise several degrees ($T_0 \rightarrow T_{a2}$), however this energy is not wasted. Several degrees higher than cold water temperature (T_0) will not influence the adsorption refrigeration much, this might be even better than normal cooling to the adsorption bed by natural convection. Refrigeration will continue for the whole night until the next morning. The thermodynamic cycle for adsorption refrigeration can be demonstrated in a P–T–X diagram shown as Fig. 3.

The features of the hybrid system include (1) it has two purposes: water heating and refrigeration with one solar collector, which is suitable for household applications; (2) adsorber/generator is separated from collector, thus a high efficiency vacuum collector can be used for water heating, thereby heating the adsorber at the same time. The high efficiency heating does not mean a bad

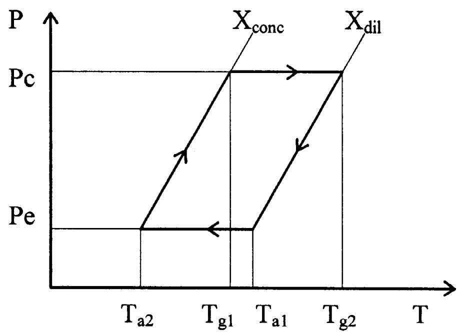

Fig. 3. Adsorption refrigeration cycle.

cooling of the adsorber through the night, as by draining the hot water from the tank, cold water is refilled to the tank, thus the adsorber is cooled and refrigeration will take place; (3) energy efficiency is high for the use of the total solar energy collected; (4) there is no danger of methanol disintegration as the maximum temperature of the adsorbent bed cannot exceed 100°C, due to the water tank.

3. PERFORMANCE SIMULATION: MODEL

3.1. Energy analysis of solar heating

Solar heating absorbed by the collector will be used in three ways: (1) Q_u, energy to heat the water tank and adsorbent bed, (2) Q_s, energy storage in the collector; (3) Q_l, energy lost due to various losses. The energy conservation equation is

$$A_e G(\tau\alpha) = Q_u + Q_l + Q_s \tag{1}$$

where G is the solar flux density to the adsorber, τ is the transmittance of solar radiation through the cover of the collector, α is the absorptance of the collector, A_e is the area of the collector.

For a plate type or evacuated tube type solar collector, the heat quantity Q_u is used to heat the water and adsorber in the water tank, which is mainly determined by the efficiency of the collector; the heat quantity Q_s is dependent on the solar collector material; Q_l is the heat losses composed of the face loss Q_t, the bottom loss Q_b, and the four sides loss Q_e. Usually Q_e is relatively smaller than Q_t and Q_b, in which Q_t and Q_b can be calculated by

$$Q_t = \int U_t A_e (T_p - T_a)\mathrm{d}t \tag{2}$$

$$Q_b = \int U_b A_e (T_p - T_a)\mathrm{d}t. \tag{3}$$

Here T_p is the average temperature of the solar collector, T_a is the environmental temperature, U_t is the heat loss coefficient of the collector face, U_b is the heat loss coefficient of the collector bottom. Of the heat losses, Q_b is usually less than 10%.

3.2. Energy analysis of the adsorber in the water tank

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

$$Q_u = \int_{T_{a2}}^{T_{g2}} M_{water} C_{water} \mathrm{d}T + \int_{T_{a2}}^{T_{g2}} (M_m C_{pm} + M_a C_{pa})\mathrm{d}T + \int_{T_{a2}}^{T_{g1}} x_{conc} M_a C_{pl} \mathrm{d}T + \int_{T_{g1}}^{T_{g2}} h_d M_a \mathrm{d}x + \int_{T_{g1}}^{T_{g2}} x(T, p_c) M_a C_{pl} \mathrm{d}T \tag{4}$$

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 remaining in the adsorbent bed. In Eq. (4), 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

$$H_d = \int_{T_{g1}}^{T_{g2}} h_d M_a \mathrm{d}x = \int_{T_{g1}}^{T_{g2}} h_d M_a \frac{\mathrm{d}x}{\mathrm{d}T}\mathrm{d}T \tag{5}$$

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

In our research, activated carbon–methanol is used as the working pair. The adsorption equation of activated carbon–methanol can be described by the following equation (Wang *et al.*, 1997):

$$x = x_0 \exp\left[-k\left(\frac{T}{T_s} - 1\right)^n\right] \tag{6}$$

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 (Wang *et al.*, 1997): $x_0 = 0.284$, $k = 10.21$, $n = 1.39$, $T_s = 288.3$ K, where Shanghai 'YK' (coconut shell type activated carbon) is used. h_d can be calculated from the Clausius-Clapeyron equation, where $T_s = T_c$ (condensing temperature):

$$h_d = RA\frac{T}{T_c} \tag{7}$$

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

3.3. Energy balance between filled water and adsorber

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 to rise 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

$$\begin{aligned} Q_c = &\int_{T_{a2}}^{T_{g2}} (M_m C_{pm} + M_a C_{pa})\mathrm{d}T + \\ &\int_{T_{a1}}^{T_{g2}} x_{dil} M_a C_{pl}\mathrm{d}T + \int_{T_{a2}}^{T_{a1}} h_a M_a \mathrm{d}x + \int_{T_{a2}}^{T_{a1}} x M_a C_{pl}\mathrm{d}T \end{aligned} \tag{8}$$

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

$$H_a = \int_{T_{a2}}^{T_{a1}} h_a M_a \mathrm{d}x = \int_{T_{a2}}^{T_{a1}} h_a M_a \frac{\mathrm{d}x}{\mathrm{d}T}\mathrm{d}T, \tag{9}$$

and 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 to increase several degrees for the water in the tank.

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

$$T_{a2} = T_0 + \frac{Q_c}{M_{water} \times C_{pwater}} \tag{10}$$

which is also the adsorption temperature for the refrigerator.

3.4. Refrigeration capacity

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

$$Q_{ref} = \Delta x M_a L_e \tag{11}$$

$$\Delta x = x_{conc} - x_{dil} \tag{12}$$

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

$$Q_{cc} = M_a \Delta x C_{pl}(T_c - T_e). \tag{13}$$

3.5. Refrigeration COP_{cycle} and system COP_{solar}

Refrigeration cycle COP can be written as

$$\mathrm{COP}_{cycle} = \frac{Q_{ref} - Q_{cc}}{Q_g} \tag{14}$$

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

$$\begin{aligned} Q_g &= Q_u - Q_{water} \\ &= \int_{T_{a2}}^{T_{g2}} (M_m C_{pm} + M_a C_{pa})\mathrm{d}T + \int_{T_{a2}}^{T_{g1}} x_{conc} M_a C_{pl}\mathrm{d}T \\ &\quad + \int_{T_{g1}}^{T_{g2}} h_d M_a \mathrm{d}x + \int_{T_{g1}}^{T_{g2}} x M_a C_{pl}\mathrm{d}T \end{aligned} \tag{15}$$

$Q_{water} = \int_{T_{a2}}^{T_{g2}} M_{water} C_{water}\mathrm{d}T$ 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 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 outputs, one is refrigeration, its solar efficiency is

$$\mathrm{COP}_{\mathrm{solar}} = \frac{Q_{\mathrm{ref}} - Q_{\mathrm{cc}}}{\int G(t)\mathrm{d}t} \tag{16}$$

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

$$\eta_{\mathrm{solar}} = \frac{Q_{\mathrm{water}}}{\int G(t)\mathrm{d}t} \tag{17}$$

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

4. 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. The configuration of the system is shown in Fig. 2.

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 $\int G(t)\mathrm{d}t = 20\ \mathrm{MJ/m^2}$ 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 2 m^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 20 $\mathrm{MJ/m^2}$ per day has been assumed, this value will be changed for the real four seasons. However the simulation results show that about 6–10°C temperature increase in the 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 especially in summer time.

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

Materials	Mass (kg)	Specific heat (J/kg K)
Adsorbent carbon	$M_{\mathrm{a}} = 28$	$C_{\mathrm{pa}} = 900$
Adsorber stainless steel	$M_{\mathrm{m}} = 5$	$C_{\mathrm{pm}} = 902$
Water in the tank	$M_{\mathrm{water}} = 50$	$C_{\mathrm{pwater}} = 4180$

Methanol: $C_{\mathrm{pl}} = 750$ (J/kg K), $x_0 = 0.284$ kg/kg, $k = 10.21$, $n = 1.39$,
$T_{\mathrm{s}} = 288.3$ K, $A = 4413$, $L_{\mathrm{e}} = 1102$ (kJ/kg).

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

Seasons	Jan–March	April–June	July–Sept	Oct–Dec
Filled water temp. T_0 (°C)	10	15	25	10
Condensing temp. T_{c} (°C)	20	25	35	15
Evaporation temp. T_{e} (°C)	−10	−10	−10	−10
Adsorption temp. T_{a2} (°C)	19.6	23.7	31	19.5
Generation temp. T_{g2} (°C)	86.6	93.1	100	84.9
$\mathrm{COP}_{\mathrm{cycle}}$	0.48	0.44	0.32	0.51
$\mathrm{COP}_{\mathrm{solar}}$	0.042	0.044	0.038	0.046
η_{solar}	0.372	0.361	0.341	0.370
Ice made per day (kg)	7.9	6.3	3.05	8.7

5. EXPERIMENTS

The concept design of the hybrid system shown as Fig. 2 did not prove successful, the reason is that the heat transfer in the activated carbon bed is very bad, which causes heating and cooling of the adsorbent to be a big problem. There are two solutions to solve this problem, one is to have a compressed adsorbent bed with heat transfer enhancement, another is to have an adsorber in which the adsorbent bed is much thinner, thus good heat transfer can still be guaranteed.

A modified prototype hybrid system for water heating and ice-making has been developed, the adsorber consisted of 28 $\phi 50 \times 1 \times 750$ mm stainless steel tubes, in which 22 kg activated carbon was filled, the adsorber mass is about 25 kg. The water tank is filled with 120–150 kg water. A 1500 W electric heater is used to simulate a 3 m^2 vacuum heat pipe type solar collector. Fig. 4 shows the simulation hybrid system.

A typical experiment is demonstrated, the initial water temperature in the water tank is 18°C, and the initial adsorbent temperature is 20°C. After 6 h heating, the 150 kg water bath temperature reaches 81°C, and the adsorbent temperature reaches 72°C. The desorption process starts, in a 4-h desorption process heating of the water bath continues. The stop point of heating is 98°C for the water bath, the corresponding desorption temperature is 89°C. The desorbed methanol is 4.1 l, about 3.3 kg. About 54 MJ heat is added in the 10-h heating–desorption process.

The hot water was taken away in the evening at 20:00 h, then the city water with a temperature of 10°C was filled into the tank, the adsorbent bed temperature was thereby reduced to 27.4°C. Meanwhile about 15 kg water with a temperature

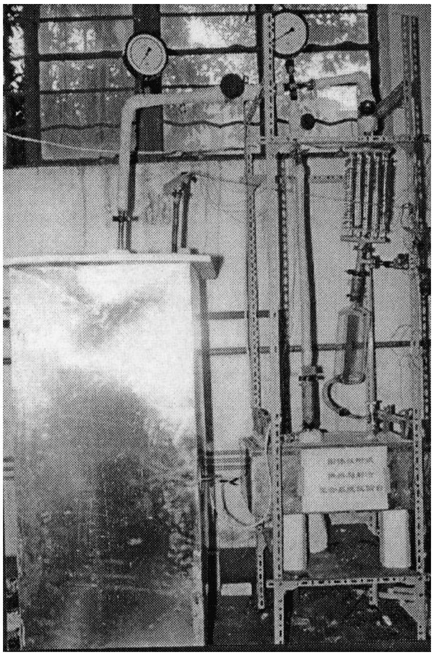

Fig. 4. The prototype of hybrid water heating and adsorption ice maker.

of 15°C was filled into the ice box. Adsorption refrigeration was then initiated, which lasted until the second morning at 08:00 h. We measured the water bath temperature raised up to 17.4°C, the adsorbent temperature decreased to 22°C. It was found that 10.5 kg ice with a temperature of −2.5°C had been made.

Here the definition of COP and η corresponding to Eqs. (16) and (17) are

$$\mathrm{COP}_{\mathrm{heating}} = \frac{Q_{\mathrm{ref}} - Q_{\mathrm{cc}}}{Q_{\mathrm{T}}} \tag{18}$$

$$\eta_{\mathrm{heating}} = \frac{Q_{\mathrm{water}}}{Q_{\mathrm{T}}} \tag{19}$$

where Q_{T} is the total heat added from the heater to the water bath. It was evaluated that the adsorption refrigeration COP driven by heating is $\mathrm{COP}_{\mathrm{heating}} = 0.067$, and the heating efficiency is $\eta_{\mathrm{heating}} = 0.906$. The adsorption refrigeration cycle COP has been calculated as $\mathrm{COP}_{\mathrm{cycle}} = 0.386$.

Table 3 shows the two experimental results of hot water and ice output in two typical seasons: winter and spring. The water bath is relatively big, in which 150 kg water and 112 kg water were filled for testing. In order to get the design value in which hot water output is about 60 kg with a 2-m^2 solar collector heat input, we have made a calculation based upon the above tests shown in Table 3; Table 4 shows the results. Here 60 kg water is assumed in the water bath, the energy accepted is about 22–24 MJ per day, which is a simulation to a 2-m^2 solar collector. The calculated results show that a 2-m^2 solar collector is capable of heating 60 kg water to about 90°C and producing ice for about 10 kg.

Attention should be drawn to the fact that the simulation prototype system of water heating is in an open tank, in which the cover of the tank is not sealed, which caused several percent heat dissipation by evaporation of water. The value of η_{system} is thus smaller than the ideal system, so is the $\mathrm{COP}_{\mathrm{system}}$.

6. CONCLUSION

A hybrid system of solar powered water heater and refrigerator has been described, which is capable of both heating and cooling effects. With

Table 3. The experimental results of the hybrid system

Experimental date	Energy accepted (MJ)	Hot water output		Ice output		$\mathrm{COP}_{\mathrm{system}}$	$\mathrm{COP}_{\mathrm{cycle}}$	η_{system}
		°C	kg	°C	kg			
Dec. 9–10, 1998	54	98	150	−2.5	10.5	0.067	0.386	0.906
March 10–11, 1999	49	91.3	112	−1.8	10	0.064	0.431	0.758

Table 4. Calculated performance of the hybrid system based upon experimental results

Experimental date	Energy accepted (MJ)	Hot water output		Ice output		$\mathrm{COP}_{\mathrm{system}}$	$\mathrm{COP}_{\mathrm{cycle}}$	η_{system}
		°C	kg	°C	kg			
Dec. 9–10, 1998	24.6	98	60	−2.5	10.5	0.143	0.386	0.795
March 10–11, 1999	22	91.3	60	−1.8	10	0.144	0.431	0.797

a 2-m^2 solar collector, it is capable of making 60 kg 90°C hot water and producing 10 kg ice per day. A prototype simulation system has been constructed, which has proven the suggested idea of combined heating and cooling cycle. The hybrid system is capable of reaching a specific refrigeration density of about 0.5 kg ice/kg-adsorbent per day. The successful design of good adsorbent bed will accelerate practical application of solid adsorption refrigeration driven by solar energy.

Although this device is designed just for solar energy utilization, it can be applied to many energy saving fields such as waste heat recovery in industry, the utilization of air conditioning driven by exhaust gas of automobiles. This novel concept of energy utilization provides an efficient way for sustainable development.

It is seen that this very attractive idea is reasonable.

NOMENCLATURE

A	constant of the Clausius-Clapeyron equation
A_e	area of the solar collector (m^2)
C_{pa}	specific heat of adsorbent (kJ/kg K)
C_{pl}	specific heat of refrigerant liquid (kJ/kg K)
C_{pm}	specific heat of metallic adsorber (kJ/kg K)
C_{pwater}	specific heat of water (kJ/kg K)
COP	refrigeration COP
COP_{cycle}	refrigeration cycle COP
$COP_{heating}$	refrigeration cycle COP driven by heating
COP_{solar}	solar power refrigeration COP
$G(t)$	solar heat flux density (W/m^2)
h_a	heat of adsorption (kJ/kg)
H_a	integrated heat of adsorption (kJ)
h_d	heat of desorption (kJ/kg)
H_d	integrated heat of desorption (kJ)
k	characteristic parameter of adsorption pair
L_e	latent heat of evaporation of refrigerant (kJ/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_l	heat losses (kJ)
Q_{ref}	refrigeration effect (kJ)
Q_s	heat stored in the collector (kJ)
Q_T	total heat load (kJ)
Q_t	face heat losses (kJ)
Q_u	heat transferred to the water tank (kJ)
T	temperature (°C)
T_a	environmental temperature (°C)
T_{a1}	temperature to start adsorption (°C)
T_{a2}	adsorption temperature (°C)
T_c	condensing temperature (°C)
T_e	evaporation temperature (°C)
T_{g1}	temperature to start desorption (°C)
T_{g2}	desorption temperature (°C)
T_p	average temperature of solar collector (°C)
T_s	saturated temperature (°C)
T_0	filled water temperature (°C)
U_b	bottom heat transfer coefficient (W/m^2 K)
U_t	face heat transfer coefficient (W/m^2 K)
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)
α	absorptance
τ	transmittance
η_{solar}	solar heating efficiency
Δx	adsorption capacity difference between adsorption phase and desorption phase $\Delta x = x_{conc} - x_{dil}$ (kg/kg)

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