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Ruzhu Wang
Shanghai Jiao Tong University

Zisheng Lu
Shanghai Jiao Tong University

Liwei Wang
Shanghai Jiao Tong University

Zaizhong Xia
Shanghai Jiao Tong University

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Ruzhu Wang[1], Zisheng Lu, Liwei Wang, Zaizhong Xia
Institute of Refrigeration & Cryogenics, Shanghai Jiao Tong University, Shanghai 200030, China
(Phone: +86 21 6293 3838, Fax: +86 21 6293 2601, E-mail: rzwang@sjtu.edu.cn)

ABSTRACT

The adsorption performances of compound adsorbent (the mixing of activated carbon and $CaCl_2$ by proper technology)-ammonia are studied, which shows the obviously improvement for long term stable operation of adsorption/desorption, and also the large adsorption cooling density. A multifunction heat pipe for heat transfer design in adsorber is invented to use waste heat for heating and sea water for cooling effectively and reliably. An adsorption ice-maker experimental system driven by the exhausted heat from the diesel engine of fishing boats are studied, which shows the optimum average SCP (specific cooling power) and COP (coefficient of performance) for the refrigerator have reached to 770.4W/kg and 0.39 respectively at about -20^{o}C evaporating temperature.

Based upon the studies above, a real multifunction heat pipe adsorption icemaker is then designed and built, the system is fully automatic controlled by Programmable Logic Controller (PLC). The system operation shows the capability to make flake ice for more than 20 kg/hr.

1. INTRODUCTION

Adsorption refrigeration systems present the advantages of being absolutely benign for the environment and having zero ozone depletion potential (ODP) as well as zero global warming potential (GWP). Adsorption refrigeration is also attractive for the efficient use of solar energy and low-grade waste heat. In the last two decades, adsorption refrigeration has been paid a lot of attentions. Compared with the existing absorption systems and vapor compression refrigeration systems, the advantages of adsorption systems are less vibration, simple control, low initial investment and expenditure, and less noise (Wang, et al, 2002, Wang, et at 2003).

Adsorption working pairs for adsorption refrigeration include physical adsorption working pairs, chemical adsorption working pairs and compound adsorption working pairs. The researches on physical adsorption working pairs mainly focus on the application of solar energy, such as activated carbon-ammonia and activated carbon-methanol for solar refrigeration systems, silica gel-water and zeolite-water for solar air-conditioning. Typical studies are those of Tamainot-Telto et al.(1997), Critoph et al.(1986), Pralon et al. (2000), Wang et al. (2003), Critoph et al. （2004）, Lu et al. （2004） and so on. The merit of chemical adsorbents is largely in their adsorptive capacity. The defects of chemical adsorbents are critical problems of heat transfer and gas permeability, as well as the problems of expansion and agglomeration （Wang, 2004）. Compound adsorbents have the advantages of both porous medium and chemical adsorbent. S. Mauran et al. （1996） studied the graphite-chemical compound adsorbents, and results show that compound adsorbent could improve the heat and mass transfer performance significantly. Wang et al (2004), Lu et al (2006) and Wang et al (2006) have researched in the consolidated compound adsorbent, which is composed of calcium chloride and activated carbon, and the results show that consolidated compound adsorbent could improve the mass transfer performance and specific volume cooling quantity of adsorbent greatly.

Various methods are used to improve the performance of adsorption refrigeration systems. For example finned

[1] Corresponding author, rzwang@sjtu.edu.cn

tubes, plate heat exchanger, heat pipe theory, etc are used in the design of adsorption beds to improve mass and heat transfer performance. Wang et al. （2002） incorporated heat and mass recovery processes into the continuous cycle. Most of the advanced cycles have been proposed with the purpose of achieving either high *COP* or *SCP* values. Based on the outstanding work of the previous researchers, this paper presents the design and experiment of a product of a multifunction heat pipe adsorption experimental refrigerator and an ice-maker for fishing boat, which is driven by waste heat from exhaust gases and its effect on the system performance is analyzed. $CaCl_2$/activated carbon is used as compound adsorbent, ammonia as adsorbate.

2. COMPOUND ADSORBENT

Adsorber is the most important part in the adsorption refrigeration system. In this system, the adsorber is designed as Fig. 1. There are 19 finned tubes and 12 vapor-distributing tubes in each adsorber.

The consolidated adsorbent of $CaCl_2$ and activated carbon is used as adsorbent, which has a high volume adsorption capacity while avoiding the problems of agglomeration and performance attenuation. Here, $CaCl_2$ powder, coconut shell activated carbon and a small quantity of high-quality cement are mixed and compacted together in a consolidated adsorbent in that mixture, the cement acts as binder, as shown in Fig. 1-A. The mass fractions of $CaCl_2$, activated carbon (before be purified) and cement in the consolidated compound, are in the proportion of 16:4:1, respectively. The consolidated compound adsorbent is pressed inside fins, as shown in Fig. 1-B, and then the mesh and metal screen are covered in order to avoid the adsorbent leak from finned tubes, as shown in Fig. 1-C. At last, these tubes are welded between the cover plates in the adsorber, as shown in Fig. 1-D. The structure of the adsorber is shown as Fig. 1-E.

1-A 1-B 1-C 1-D 1－E

Fig.1. Manufacture of the adsorber (1-A: The composition of compound adsorbent, 1-B: The compound adsorbent was pressed between the aluminum fins, 1-C: The mesh and metal screen are covered over the aluminum fins, 1-D: The insider of the adsorber, 1-E: The structure of the adsorber)

1 heat pipe liquid pipeline, 2 heat pipe vapor pipeline, 3 end plate 1, 4 cover plate 1, 5 cover plate 2, 6 vapor distributing tubes, 7 finned tubes, cover plate 3, 9 end plate 2, 10 heat recovery pipeline, 11 heat pipe vapor pipeline, 12 temperature sensor, 13 ammonia pipeline.

3. MULTIFUNCTION HEAT PIPE ADSORPTION REFRIGERATION SYSTEM

There are four main processes in the work of this system. They are the processes of heat pipe heating, heat pipe cooling, mass recovery and heat pipe heat recovery.

1) The process of heat pipe heating: The heating boiler serves as the evaporating part of heat pipe; adsorber

serves as condensing part of heat pipe. The heat pipe liquid is heated by the heating boiler and then evaporates, the vapor then enters the adsorber through the vapor-distributing tubes, and condenses inside the finned tubes in adsorber to provide desorption heat. At last the heat pipe liquid returns to the heating boiler to be heated again.

2) The process of heat pipe cooling: Before this process, the hot adsorber is connected to the cooler. As result, the pressure prevailing therein is lower than that in the boiler. So, the heat pipe liquid can easily be pumped from the liquid pumping boiler into the adsorber.

During the process of heat pipe cooling, the hot adsorber serves as the evaporating part of heat pipe; cooler serves as condensing part of heat pipe. The heat pipe liquid evaporates in the adsorber, bring the adsorption heat out of adsorber, then enters the cooler and condenses in the cooler, the condensed liquid then returns to the adsorber again.

3) The process of mass recovery: The mass recovery process utilizes the pressure difference to enhance the refrigerant mass circulation. In mass recovery process, the valve between the hot adsorber and the cold adsorber is opened, and the ammonia vapor in the hot adsorber will enter the cold one quickly.

4) The process of heat pipe heat recovery: In the process of heat pipe heat recovery, the hot adsorber serves as the evaporating part of heat pipe while the cold adsorber serves as condensing part of heat pipe. The heat pipe liquid evaporates in the hot adsorber, then enters the clod adsorber, condensing there and transferring heat from hot adsorber to the cold adsorber, then the heat pipe liquid returns to hot adsorber again. Thus heat pipe heat recovery circuit is formed.

4. MULTIFUNCTION HEAT PIPE ADSORPTION REFRIGERATION EXPERIMENTAL SYSTEM

The average cooling power is calculated by the liquid level changes measured from the level sensor. The adsorption quantity is tested by the magnetostriction level sensor inside evaporator with relative measuring error of less than 0.05%. The diameter of evaporator is given, that is 117mm.

The averaged *SCP* is

$$SCP = 1000\frac{h_{fga}\rho_l V_l}{m \cdot t} \tag{1}$$

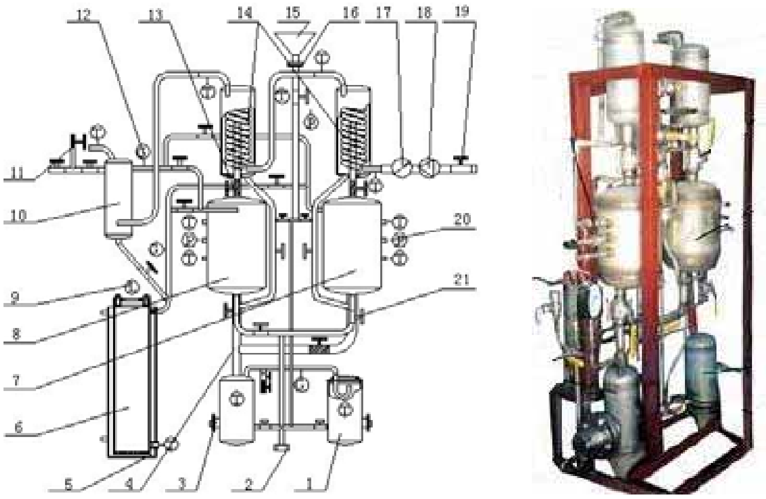
Where *SCP* is in (W/kg), m is the mass of $CaCl_2$ in compound adsorbent for each adsorber (1.88 kg), h_{fga} is the latent heat of vaporization at evaporation temperature of ammonia (kJ/kg), ρ_l is fluid density of ammonia at evaporation temperature (kg/m^3), V_l is the evaporated liquid volume of ammonia for the phase of adsorption (m^3), and t is the corresponding adsorption time (s). The coefficient of cooling performance is:

$$COP = \frac{h_{fga}\rho_l V_l}{(t - t_r)w_k} \tag{2}$$

Where *COP* is the coefficient of performance; t cycle time (S); t_r the time of heat and mass recovery (S); w_h heat power (kW)

4.1 System Design

The multifunction adsorption system is shown in Fig.2, which is mainly composed of a liquid pumping boiler, a heating boiler, two coolers, two adsorbers, a condenser, and an evaporator. This system was originally developed as an adsorption ice-maker for fishing boats, in which the waste heat from the exhausted gases of diesel engine can be used to heat the adsorber, and the sea water can be used to cool the adsorber. As steel adsorber is used for compound adsorbent-ammonia, the exhausted gases and also the sea water can not be used for direct heating and cooling. By proper design of a heat pipe unit, heating or cooling of the adsorber is via the heat pipe working substances, such as water and acetone etc.



2-A 2-B

Fig.2. Structure of the refrigeration system. (2-A:schematic diagram,2-B:photo of the system)

1-liquid pumping boiler; 2-tap-hole; 3-electric heater; 4-gas circuit of heat pipe; 5-temperature sensor; 6-glycol jacket evaporator with liquid level sensor insert; 7-adsorber1; 8-adsorber2; 9-magnetostriction level sensor;10-condenser; 11-safety valve; 12-manometer; 13-gas circuit of heat pipe;14-cooler; 15-hopper; 16-flange;17-flowmeter of cooling water;18-water pump; 19-valve;20-pressure sensor; 21-liquid circuit of heat pipe.

4.2 Dynamic Characteristics of Mass and Heat Pipe Heat Recovery

The working condition of mass recovery is: water heat pipe, 40 seconds of mass recovery time, 70 minutes of cycle time, 3.64 kW of heating power, about 110^{o}C of desorption temperature, -15 ^{o}C of evaporating temperature, 30 ^{o}C of cooling water temperature. And the working condition of heat pipe heat recovery is: water heat pipe, 40-second mass recovery, 70 minutes of cycle time, 3.64 kW of heating power, -20^{o}C of evaporating temperature, 20^{o}C of cooling water temperature, 2 minutes of heat recovery.

The Clausius-Clapeyron diagrams with and without mass recovery is shown in Fig. 3 and the Clausius-Clapeyron diagram with and without heat recovery is show in Fig.4, respectively.

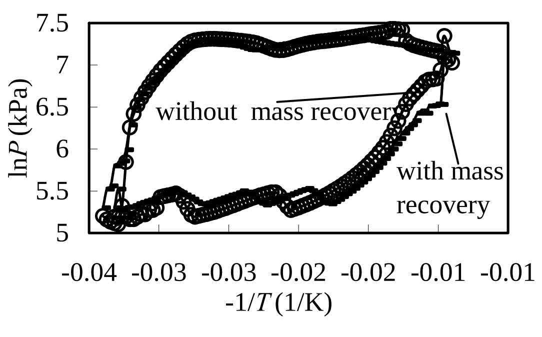


Fig.3. Clausius-Clapeyron diagram with and without mass recovery

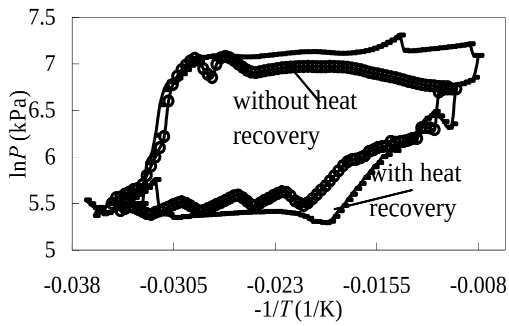


Fig. 4. Clausius-Clapeyron diagram with and without heat recovery

Fig.3 shows that in adsorption phase, the adsorber pressure of the cycle with mass recovery is lower than that of cycle without mass recovery. Fig.4 shows that in desorption phase, the adsorber pressure of the cycle with heat recovery is higher than that without heat recovery and in adsorption phase, the adsorber pressure of the cycle with heat recovery is lower than that without heat recovery. And it also shows that by heat recovery, the adsorber temperature maximum is increased and the adsorber temperature minimum is reduced in the fixed cycle time.

4.3 The Adsorption Ice-Maker with Mass and Heat Pipe Heat Recovery

This novel design of multifunction heat pipe type adsorption ice-maker is considered for possible application in fishing boats, and the normal fishing period is from January to June and from September to November and corresponding seawater temperature is about from 15 ^{o}C to 30 ^{o}C. Adsorber temperature falls down with the cooling water temperature. In water heat pipe adsorption ice-maker, the adsorption ice-maker refrigeration performance with mass and heat pipe heat recovery for fishing boats is studied. The working condition is: 70-minute cycle time, 40-second mass recovery; 2-minute heat recovery; about -20^{o}C evaporating temperature, 15~30^{o}C cooling water temperature.

The performance of adsorption refrigeration is shown in Table 1, which shows that the averaged *SCP* and the *COP* increase when the temperature of cooling water decreases. But at the condition of highest temperature of cooling water of 30 ^{o}C, the averaged *SCP* and the *COP* is still as high as 528W/kg and 0.26 respectively.

Table 1 Averaged *SCP* variation with different cooling water temperature

Cooling water temperature (^{o}C)	Evaporating temperature (^{o}C)	Desorption temperature (^{o}C)	Heating power (kW)	Averaged *SCP* (W/kg)	*COP*
20	-21.3	114.7	3.64	770.4	0.39
25	-18.1	114.0	3.64	676.8	0.34
30	-19.4	113.7	3.64	528.0	0.26

5. MULTIFUNCTION HEAT PIPE ADSORPTION ICEMAKER SYSTEM

The second adsorption icemaker system aims at improving the performance of adsorption refrigeration by applying three-dimensional finned tubes to enhance heat transfer and PLC for autocontrol. Moreover, many experiments have been done to analyze the influence of operating conditions (cooling water temperature, mass recovery and heat pipe heat recovery, etc) on the mass of ice, *SCP* and *COP*.In this experiment, the adsorber is heated by electric heater, and the temperature of the cooling water is controlled by the constant temperature cabinet.

The performance parameters of this system are the specific cooling power (*SCP*) and the coefficient of performance (*COP*). They can be measured by the following formulas:

The average *SCP* is calculated by the formula (3):

$$SCP = 1000\frac{m_w C_w T_{in} + m_w \lambda + m_w C_i (T_s - T_i)}{m_a \cdot t} \tag{3}$$

Where *SCP* is at (W/kg), m_w is the mass of the ice (kg), C_w is the specific heat of water (kJ/kg.^{o}C), T_{in} is the inlet temperature of the chilled water(^{o}C), λ is the heat of solidification of water(kJ/kg), *Ci* is the specific heat of ice(kJ/kg.^{o}C), T_s is freezing temperature (^{o}C), T_i is the ice temperature(^{o}C), *t* is the half cycle time (S), m_a is the mass of the adsorbent in each adsorber(kg).

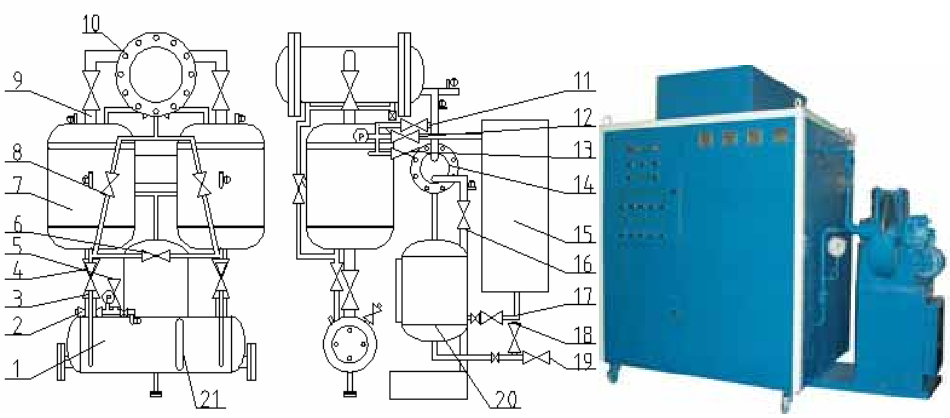
The coefficient of cooling performance (*COP*) is calculated by the formula (4):

$$COP = \frac{m_w C_w T_{in} + m_w \lambda + m_w C_i (T_s - T_i)}{\int w_h dt} \tag{4}$$

Where COP is the coefficient of performance, w_h is heating power (kW), t is heating time (S).

5.1 System Design

This system is shown in Fig. 5, which consists of six main parts: one boiler, two adsorbers, one cooler, one condenser, one ammonia storage tank and one ice-maker.



5-A 5-B

Fig. 5. The photos of adsorption icemaker system (5- A:schematic diagram, 5-B:photo of the system)

1 heating boiler, 2 prefill valve for heat pipe liquid（water）, 3 heating vapor pipeline, 4 heating liquid pipeline, 5 safety valve for boiler, 6 heat pipe heat recovery pipeline, 7 adsorber, 8 cooling liquid pipeline, 9 cooling vapor pipeline, 10 cooler, 11 mass recovery pipeline, 12 pipeline for adsorption, 13 pipeline for desorption, 14 condenser, 15 flake icemaker, 16 pipeline for cooling water, 17 ammonia restrictive valve, 18 safety valve for condenser, 19 prefill valve for ammonia, 20 ammonia liquid receiver, 21 viewing mirror for boiler

5.2 Performance Variation With Mass Recovery

The icemaker with mass recovery process utilizes the pressure difference to enhance the refrigerant mass circulation. As it is shown in our previous publication, mass recovery can not only improve the adsorption refrigeration performance significantly, but can also recover much of heat of adsorption. The inlet and outlet water temperatures of condenser are studied, as shown in Fig. 6. During the mass recovery, the high temperature ammonia vapor has entered the low pressure adsorber. So, from the Fig. 6, we can see that the outlet water temperature with mass recovery is lower than that without mass recovery. By the calculation of the formula (5), the cooling power of the condenser can be reduced by 28.4% after 40 seconds of mass recovery.

$$q_r = m_r C_r (T_{ro} - T_{ri}) \tag{5}$$

Where q_r is the cooling power (kW), m_r is the mass flow of cooling water (kg/S), C_r is the specific heat of water (kJ/kg.^{o}C), T_{ro} is the outlet water temperature (^{o}C), T_{ri} is the inlet water temperature (^{o}C).

The performance of the mass recovery varies with the mass recovery time. If the time is too short, the mass of the ammonia can not be recovered adequately. Otherwise, when the time is too long, the time for adsorption/desorption will be shortened relatively. Reference (Akahira et al, 2004) shows that the more cooling capacity can be obtained by applying heating and cooling in mass recovery process. The continuation of heating and cooling increases a quantity of ammonia vapor moving from desorber to adsorber, which will lead the system to provide better cooling capacity.

In this experiment, the adsorption performance variation with different mass recovery is studied, as shown in table 2. Table 2 shows the adsorption refrigeration performance of the cycle with 40 S of mass recovery with heating and cooling is the better than the others.

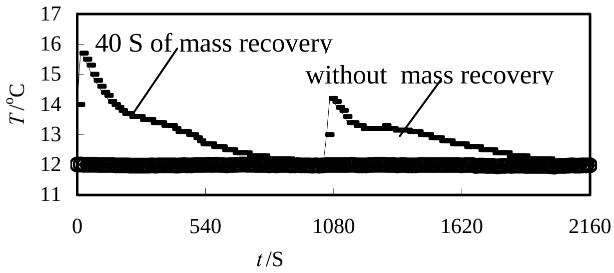


Fig. 6. The inlet/outlet water temperature of the condenser.

Table 2 The performance variation with different mass recovery
(The ice temperature is about -7.5°C; the desorption temperature of the absorber is about 126°C and the adsorption temperature of the adsorber is about 38 °C)

Mass recovery (S)	Heat recovery(min)	Cycle time (min)	Mass of ice(kg/h)	*SCP* (W/kg)	*COP*
20	2	36	22.9	429.8	0.3
40	2	36	25.4	476.1	0.3
40(with heating &cooling)	2	36	26.1	494.5	0.3
60	2	36	24.3	456.3	0.3

5.3 Performance Variation With Heat Pipe Heat Recovery

The heat pipe heat recovery can bring about two merits. Firstly, by heat pipe heat recovery, much heat can be recovered. Secondly, after the process of heat pipe cooling, the adsorber is heated for desorption and water in the adsorber is discharged to boiler, that will descend boiler water temperature. Boiler water temperature of the cycle with heat pipe heat recovery is higher than that without heat recovery, because water is preheated by the process of heat pipe heat recovery.

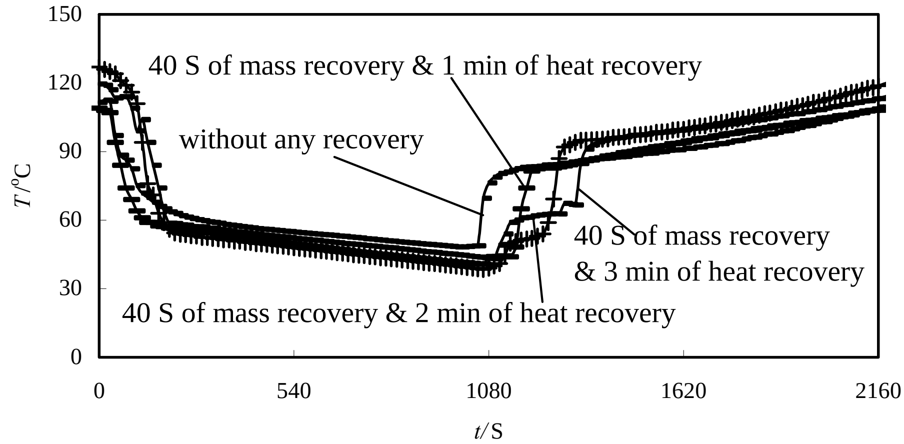


Fig. 7. The adsorber temperature variation with different heat pipe heat recovery time

In this experiment, the adsorber temperature variation with different heat pipe heat recovery time is shown in Fig. 7, which shows that the 2 minutes of the heat recovery is the better choice than the others. By 2 minutes of the heat pipe heat recovery, the adsorber temperature can reach a lower value during the cooling phase and it can get a higher temperature during the heating phase. The adsorption performance of the icemaker with different heat recovery time is shown in table 3.

Table 3 The adsorption performance of the icemaker with different heat recovery time
(12^{o}C of the cooling water temperature, and -7.5^{o}C of the ice temperature)

Heat recovery(min)	Mass recovery(S) (With heating and cooling)	Cycle time（min）	Mass of ice(kg/h)	*SCP* (W/kg)	*COP*
1	40	36	19.8	377.6	0.2
2	40	36	26.1	494.5	0.3
3	40	36	21.5	407.6	0.2

5.4 Performance Variation With Different Sea Water Temperature

The adsorption performance variation with different sea water temperature is shown in Table 4, which shows that the average *SCP* and *COP* increase as the temperature of cooling water decreases.

Table 4 The adsorption performance variation with different sea water temperature
(The ice temperature is about -7.5 ^{o}C)

Cooling water（^{o}C）	Heat recovery(min)	Mass recovery(S) (with heating and cooling)	Mass of ice(kg/h)	*SCP* (W/kg)	*COP*
27	2	40	14.8	324.6	0.2
22	2	40	17.6	369.1	0.2
17	2	40	22.2	443.0	0.3
12	2	40	26.1	494.5	0.3

6. CONCLUSIONS

In the first experimental test unit, the multifunction heat pipe adsorption system is designed and established, and dynamic characteristics of mass and heat pipe heat recovery are analysed. Then a real multifunction heat pipe adsorption icemaker is designed and built. Several conclusions obtained are as follows:

1) The process of mass recovery can not only improve the adsorption performance, but can also recover much of heat of adsorption.

2) The process of heat pipe heat recovery can recover much of heat. During this process, the hot adsorber is pre-cooled and the cold adsorber is preheated.

3) The adsorption performance varies with different sea water temperature. The average *SCP* and *COP* increase as the temperature of cooling water decreases. In the first experimental test unit, At the condition of highest temperature of cooling water of 30 ^{o}C, lowest averaged *SCP* and *COP* are still as high as 528kg/kg and 0.26, respectively. In the real icemaker system, when the sea water is about from 27^{o}C to 12^{o}C, the *SCP* varies from 324.6 W/kg to 494.5W/kg and the *COP* varies 0.2 to 0.3, respectively.

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