EFFICIENT ADSORPTION REFRIGERATORS INTEGRATED WITH HEAT PIPES

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Abstract

Several novel ideas to use heat pipes in adsorption water chiller or ice maker are presented in this paper. Experimental results have shown that the adsorption refrigerators are very efficient. The first example of such systems is a small scale silica gel-water adsorption water chiller with cooling power rated as 10 kW, the system could be powered by 60-100 °C hot water, a cooling COP=0.4 has been achieved when driven by 85 °C hot water. This adsorption chiller have been used for solar powered air conditioner and also as the chiller for CCHP system. The second example is a silica gel-water adsorption room air conditioner powered by 80 °C hot water, the system is very compact and is suggested for potential applications of micro CCHP system based on fuel cells. The system has a COP over 0.3 and cooling power about 1 kW. The third example is the use of split heat pipes to heat or cool adsorber for ice making in fishing boat. The application of these technologies avoid the corrosion of adsorber at the heating phase by exhausted gases and at the cooling phase by seawater, and also has the advantage of high heat transfer performance. With such arrangement and careful considerations of the arrangement of wicks in heat pipes, and also the use of composite adsorbent (calcium chrolide and activated carbon)-amminia adsorption pair, the system test has shown the specific refrigeration power for more than 730W/kg at –15 °C.

KEYWORDS

Adsorption refrigerator, heat pipe, chiller, ice maker.

INTRODUCTION

As an environmental benign energy utilization system, adsorption refrigeration has got enough attentions for research and development [1]. Facing the real applications, three research directions have been considered: 1) the use of solar energy for air conditioning, in which 60-90 °C solar heated hot water could be easily used; 2) the efficient use of waste heat recovered for cooling. For example the waste heat from engines ranging from 80 - 500 °C, in which various adsorption refrigeration pairs could be selected. The typical examples are adsorption chiller based CCHP systems, adsorption ice maker for fishing boat powered by the exhausted gases from diesel engine; 3) adsorption heat pumping, in which a heating COP is always large than 1 and adsorption system is more easy to deal with in comparison with liquid absorption systems.

Facing the real applications of adsorption systems, the selection of proper adsorption pairs, the heat and mass transfer enhancement in adsorption bed, and the invention of advanced adsorption refrigeration cycles are always the research interests. The research group of the author has started such work since 1993, and has developed a lot of adsorption systems such as solar adsorption ice maker (activated carbon-methanol) [2], hybrid system of solar water heating and adsorption ice maker (activated carbon-methanol) [3], double bed adsorption ice maker powered by hot water (activated carbon-methanol) [4], double bed heat regenerative adsorption heat pump (activated carbon-methanol) [5], adsorption air conditioner for locomotive cabin powered by the waste heat of exhausted gases (zeolite-water) [6, 7], adsorption ice maker for fishing boat (activated carbon integrated bed-methanol) [8].

In the development of such systems, granular bed were usually used, the cycle time is usually between 30-60 minutes. If the adsorber is designed carefully concerning heat and mass transfer, the cycle time could be shortened to 10-20 minutes. This has been shown in the performance silica gel-water adsorption chiller, in which plate-fin heat exchanger has been used as an adsorber [9]. But for the 4-10 kW adsorption water chiller, complicated piping and switch valves are necessary together with pumps to drive heating/cooling/chilling mediums, the chilled water cooling power was output from the two evaporator alternatively. This arrangement may increase the cooling losses and also consume the electric power for the pumps.

In the development of adsorption ice maker, activated carbon compressed and integrated was used successfully, in which methanol was used as refrigerant, a 2 kW ice maker has been demonstrated [8]. In this system, a waste heat recovery boiler, a two-bed adsortion refrigeration system and a flake ice maker were used. The design of this system is a traditional one though the heat and mass transfer in adsorption beds were enhanced [10]. The system is prepared for adsorption ice maker for fishing boat in which the exhausted gases waste heat is available to power the ice maker system and sea water is easily got to cool the adsorber. But the direct heating by exhausted gases and direct cooling by seawater will cause serious corrosion problems.

Heat pipes are reasonable for cooling and heating in adsorption refrigeration systems, not only due to its high heat flux density, but also due to its no moving parts to drive heat transfer medium. Vasiliev et al. have successfully demonstrated to use heat pipes for adsorption refrigerators [11, 12]. By the way, with good design ideas, it is possible to use split type heat pipes to heat or cool adsorbers, which makes adsorbers contact with heat pipe working medium for heating and cooling, in this case heating with exhausted gases and cooling with sea water could be conducted to an adsorber. Several novel ideas to use heat pipes in adsorption water chiller or icemaker are presented in this paper. Experimental results have shown that the adsorption refrigerators are very efficient.The detailed work of such systems and other adsorption refrigerators integrated with heat pipes are shown in this paper.

SILICA GEL – WATER ADSORPTION CHILLER WITH GRAVITY HEAT PIPE COOLING OUTPUT

The first example of such systems is a small scale adsorption refrigeration water chiller with cooling power from 5-200 kW. Such systems needs continuous colling output and low or no consumption of electric energy. Fig. 1 and Fig. 2 show the drawing and photo of the heat pipe type adsorption chiller driven by low temperature heat source. There are two vacuum chambers inside this chiller, each of them encloses one adsorber, one condenser, and one evaporator. Mass recovery piping [13] is installed between the two chambers. Cooling power of this adsorption chiller is 6~10 kW. The 6 kW cooling power and COP about 0.35 are obtained when the system is powered by hot water at 65 °C, which is the lowest working temperature of hot water, while 10 kW cooling power and COP about 0.4 are obtained when the temperature of hot water is 85 °C. This adsorption chiller could be used for solar powered air conditioner and also as the chiller for CCHP system. Adsorption system could provide 10~15 °C chilled water for normal air conditioning systems, or 15~20 °C chilled water for dry fan coils cooling according to the requirements in which COP about 0.5 could be reached.

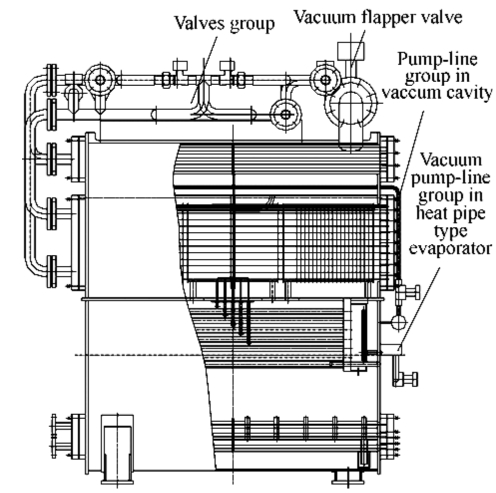


Fig. 1. Adsorption chiller with heat and mass recovery and heat pipes to output cooling

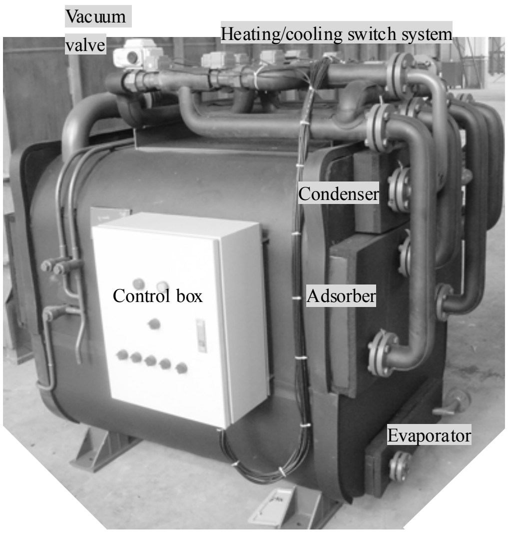


Fig. 2. Photograph of the heat pipe type silica gel-water adsorption chiller

Fig. 3 shows the structure of the heat pipe type silica gel-water adsorption chiller. This silica gel-water adsorption chiller is composed of three working vacuum chambers including two desorption/adsorption chambers and one heat pipe working chamber. In the adsorption chamber, water is taken as the refrigerant, while in the heat pipe working chamber, methanol is used as the working substance.

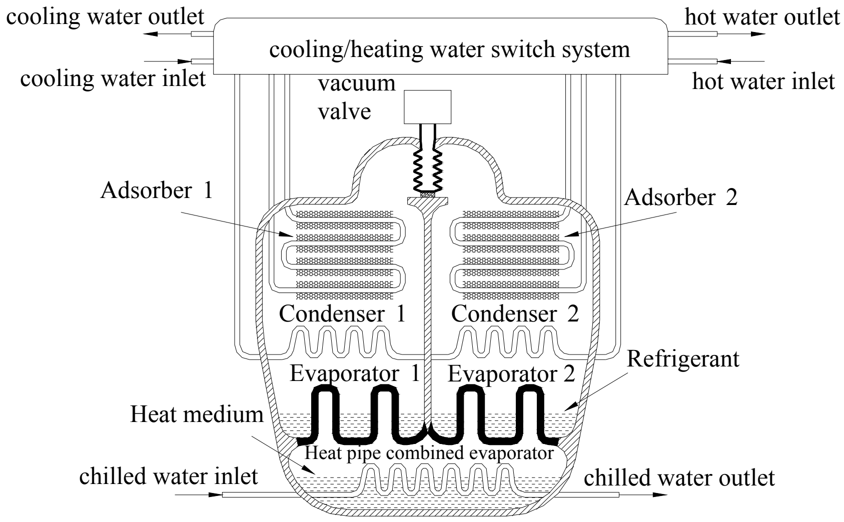


Fig. 3. Schematic diagram of the heat pipe type silica gel-water adsorption chiller

The evaporation cooling in evaporator 1 or 2 is transferred to the methanol chamber via heat pipe evaporation/condensation process. Chilled water is cooled down in the methanol chamber directly. This design idea has made two water evaporators (WE1, WE2) integrated into one methanol evaporator(ME).

Fig. 2 has shown the photograph of the heat pipe type silica gel-water adsorption chiller (two adsorbent bed, each contains 50 kg silica gel). The adsorbers, the condensers and the evaporator are housed by a steel shell and divided into three chambers by clapboards. The evaporator lies in the bottom of the chiller and the condensers locates in the upper. The heating/cooling switch system and the vacuum valve are on the top. All the valves are controlled by a PLC in the control box. In order to improve the performance and increase the adaptability to a low temperature heat source, a vacuum valve is installed between Chamber A and Chamber B to help the chiller fulfill mass recovery process. The desorption/adsorption process is completely controlled by the electric valves in the heating/cooling water system. So such structure of the system increases the reliability of the chiller though the water evaporating and condensing area is doubled in comparison with the traditional two-bed system.

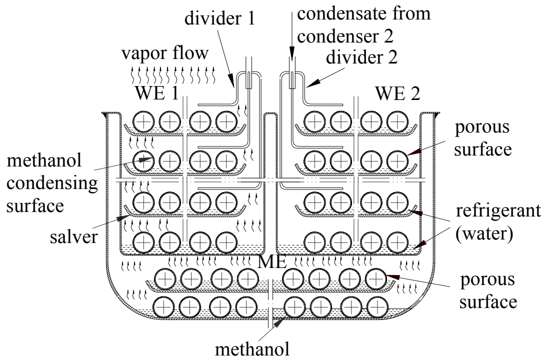


Fig. 4. Schematic diagram of the heat-pipe combined evaporator

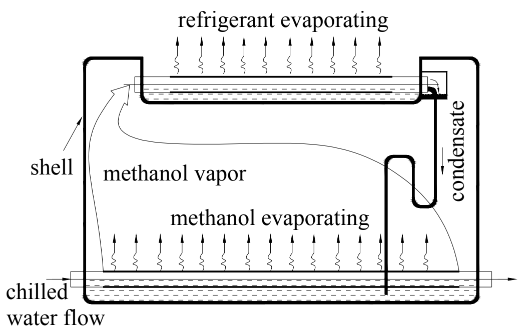


Fig. 5. Schematic diagram of the loop heat pipe used in the evaporator

The evaporators are combined together by a heat-pipe heat exchanger (HPHE), as shown in Fig. 4. The exterior surface of the copper tubes in the WE is water-evaporating surface that is porous medium to enhance the evaporating capability so that the volume of the evaporator can be minished. And the internal surface of the copper tubes is the methanol-condensing surface□plain pipe surface. The methanol will evaporate on the exterior surface of the heat exchange tubes in the ME of the HPHE and condense on the internal surface of the tubes in one WE (for example, WE1). This time WE1 is at work. Simultaneously, the WE2 collects the condensate coming from the condenser through the divider, so its temperature is higher than the temperatures of the WE1 and the ME of the HPHE. As a result, the heat exchange of the WE2 to the WE1 and the ME of the HPHE is isolated according to the working principle of a gravitation heat pipe.

Fig. 5 shows the cyclic process of the methanol inside the heat pipe. The liquid methanol evaporates on the exterior surface of the tubes in the ME, and the methanol vapor flows into the tubes in the WE from one side. After being condensed, the condensate of the methanol then returns to the ME from the other side through a U-shape tube. So this cyclic process forms a loop. As a result, the evaporator is also a looped heat pipe.

In the desorption/adsorption working chamber, the vapor channel connecting the adsorber to the condenser and the evaporator has a large through-flow sectional area. Therefore, the mass transfer from the adsorber to condenser or to the evaporator is enhanced and the potential refrigerating capacity of the adsorbent rises.

This structure of the chiller causes one evaporator and one condenser idle anytime so as to decrease the utilization ratio of the evaporators and the condensers, but four vacuum valves for the switch between adsorption and desorption process are spared. Thus, the reliability and economics of the system are improved greatly.

Fig. 6 shows the variations of chilled water and refrigerating capacity in three cycles. It indicates that this system has fine operating repeatability and stability. In one whole cycle, the chilled water inlet temperature is controlled to change a little, only 0.8 °C, but the chilled water outlet temperature will changes largely, about 6.3 °C from 14.2 °C to 20.5 °C. In adsorption process, chilled water outlet temperature quickly declines to the lowest temperature of about 14 °C and slowly rises to about 16 °C due to the weakening adsorption capability of the adsorber. The corresponding refrigerating capacity is from 14.2 kW to 8.7 kW. This temperature will sharply increase near to the inlet temperature during the mass recovery process because the evaporators have no refrigeration output in this phase. After the adsorption capacity of the desorbed adsorber is restored, the heat recovery process starts and the desorbed adsorber is cooled down to adsorption phase.

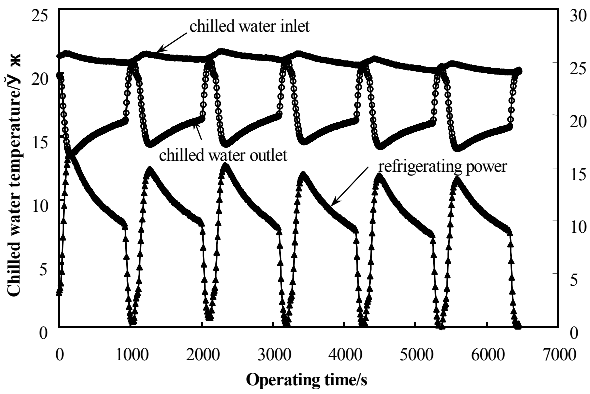


Fig. 6. Chilled water temperature and refrigerating capacity variations with operating time (heating time: 900 s; mass recovery time: 180 s)

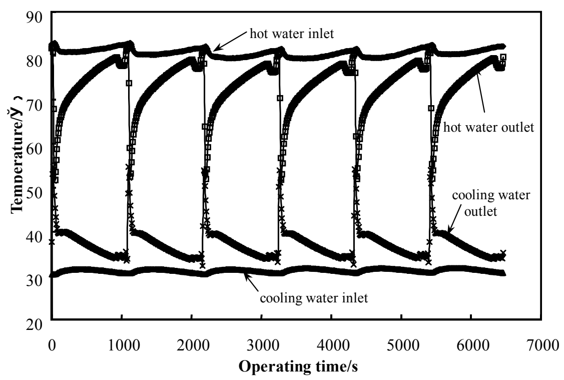


Fig. 7. Hot water and cooling water temperature variations with operating time (heating time: 900 s; mass recovery time: 180 s)

Fig. 7 shows the hot water and cooling water temperature variations with the operating time in the test. In the mass recovery process, there are interesting changes for the outlet temperatures. The hot water outlet temperature will decease first and then increase, but cooling water outlet temperature increases first and decreases at last during the mass recovery process. These temperature variations express the thermodynamic characteristics of the adsorbent beds.

Table 1 lists some experimental results of the heat pipe silica gel-water adsorption chiller. For a typical working condition with the hot water temperature of about 85 °C, SCP more than 100 W/kg could be obtained, while the COP of 0.432 is the highest. When the hot water temperature is about 60 °C, the SCP and COP will be a half of these under the typical working condition. These results indicate that both the heat pipe evaporator and the structure of the system are high effective.

Table 1. Experimental results of the heat pipe silica gel-water adsorption chiller

Hot water temp. / °C	Cooling water temp. / °C	Chilled water temp. / °C		Refrigerating power/kW	COP	SCP /W/kg	Cycle time/s
		Inlet	Outlet				
78.8	31.3	20.5	16	8.32	0.31	80	1680
81.8	31.3	20.7	16.3	9.33	0.34	89.7	1920
86.8	30.9	21.1	16.3	10.62	0.398	102.1	1920
59.7	30.4	20.5	18.2	4.80	0.385	46.2	2280
69.1	30.3	19.6	16.2	7.57	0.378	72.8	
84.4	30.5	21.5	16.5	10.88	0.432	104.6	
85.3	30.6	20.9	16.1	10.44	0.404	100.4	
80.3	30.2	15.8	12.1	8.26	0.382	79.4	
82.5	30.4	15.8	11.9	8.69	0.388	83.6	
83.8	30.8	15.4	11.8	8.6	0.383	82.7	

This adsorption chiller has been in small mass production, there are 8 units now in operation with rated cooling power of 10 kW. The manufacturer has agreed to collaborate with the author research team to extend the series as 5 kW, 10 kW, 20 kW, 50 kW, 100 kW, and 200 kW respectively.

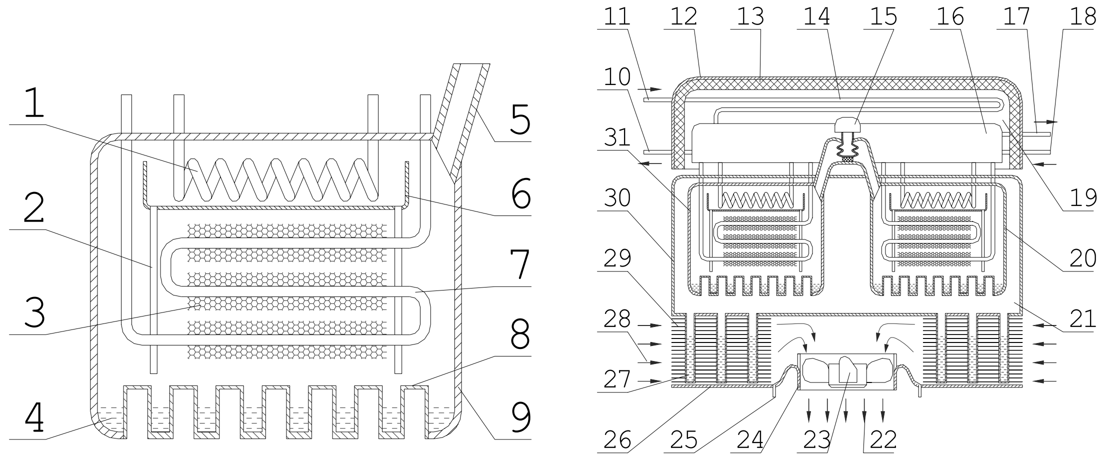
SILICA GEL-WATER ADSORPTION ROOM AIR CONDITIONER WITH DIRECT COOLING OUTPUT VIA HEAT PIPES

The compact adsorption air conditioning systems (CAACs) described in the followings now offers a new possibility to economically utilize low grade thermal energy on a large scale. The main application of CAACs is the production of cooled air. Such system could be driven by solar energy or waste heat from fuel cells or engines. One critical thing is that such small cooling power system is not suitable to output cooling by pumping chilled water through fan coils, cooling should be output to space directly, simply by a small fan to drive air to the evaporator directly, thus the electric power consumpted is very small (several ten watts).

To simplify the structure and supply cooling power continuously, a double bed adsorber system is adopted. The sketch maps of the prototype are given in Fig. 8.

The adsorber (5 kg silica gel each), condenser and evaporator are enclosed in one vacuum chamber (water vacuum chamber), thus we need not any vacuum valves between adsorber and condenser (evaporator). When adsorber is heated, the water vapor desorbed will come out from adsorber. When the vapor pressure reaches the condensation pressure, the water vapor will be condensed to liquid water. The water evaporator is designed below the condenser, so the condensed water will flow into it automatically. When the adsorbent bed is cooled, water vapor will be evaporated and adsorbed. Along with the cooling of adsorber, the pressure in the water vacuum chamber will decrease, and the water temperature in the water evaporator will decrease too. The cooling could be output to cool air. There are two water vacumm chambers in the prototype to supply cooling power continuously.

Outside the two water vacuum chambers is a methanol vacuum chamber. The function of methanol vacuum chamber is to transfer heat from the indoor air to the water evaporator. The methanol vacuum chamber is composed of two parts: methanol evaporator and methanol condenser. The methanol condenser and the water evaporator are integrated to one part that is named “separator”. When the indoor air blows through the methanol evaporator, the liquid methanol inside will evaporate, and then the methanol vapor will be condensed at the surface of the water evaporator, and the condesate will return again to the heat pipes. The methanol evaporator is composed of 50 steel tubes with aluminum fins outside. The outside surface of methanol vacuum chamber faces indoor environment directly. So, some cooling power will enter room through the surface.



a) b)

Fig. 8. A sketch map of the silica gel-water adsorption room air conditioning system. a) is the enclosed vacuum chamber integrated with adsorber, condenser and evaporator; b) is the whole structure of the two bed adsorption cooling system with cooling output by heat pipes. 1-condenser, 2-water passage, 3-silical gel, 4-water, 5-mass transfer piping, 6-water collecting plate; 7-adsorber, 8-water evaporator, 9-water vacuum chamber wall; 10,11-the outlet and inlet of cooling water tube, 12-the chamber wall of valve group, 13-heat insulation material, 14-air cooler, 15-mass transfer valve, 16-valve group; 17,18-the outlet and inlet of heating water tube,19-the chamber of valve group, 20,31-the right and left adsorption refrigeration units, 21-the methanol vacuum chamber, 22-the passage of air blowed, 23-fan, 24-air leading component, 25-water draining tube, 26-air plate, 27-the work media of heat pipe (methanol), 28-the passage of air sucked, 29-the evaporator of heat pipe (methanol evaporator), 30-the wall of methanol vacuum chamber

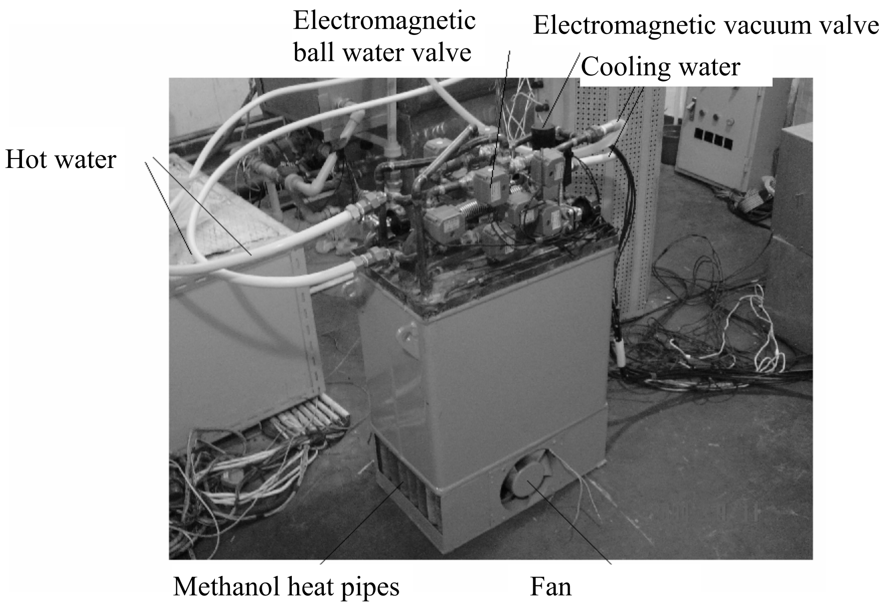


Fig. 9. The outlook of the adsorption room air conditioner prototype

Because hot water and cooling water will enter two adsorbers alternatively, it needs some water valves to switch water flow direction. The prototype has eleven electric-powered ball valves to reach the goal. There is one electromagnetic vacuum valve to connect the two vacuum chambers to performe mass recovery process.

The prototype has a size as 500 mm width, 300 mm thickness, and 950 mm height, the whole operation was controlled by a PLC controller. Fig. 9 shows the out view of the prototype.

An evaluation test has been conducted under the given working conditions. The parameters of the experiment are: flow rate of hot water: 5 Liters/min, flow rate of cooling water: 10 Liters/min, flow rate of the air flow: 4.5m^3/min, indoor air dry bulb temperature: 27°C, indoor air wet bulb temperature: 19°C. The time parameters of the experiment are as the followings:Cycle time: 38 minutes (36 minutes when the temperature of heating water inlet is 90°C), heating time of each adsorber: 15 minutes, Cooling time of each adsorber: 15 minutes, heat recovery time: 20 seconds, mass transfer time: 3 minutes (2 minutes when the temperature of heating water inlet is 90°C), the time for switching the valves: 80 seconds.

The cooling capacity and COP of various work conditions are listed in table 1 and 2 respectively:

Table 1. Cooling capacity (W)

Heating water inlet temp. °C	Cooling water inlet temp. °C		
	28	30	32
90	792.2	722.5	659.3
85	794.6	718.5	653.9
80	680.1	615	548.6
75	558	–	–
70	489.3	–	–

Table 2. Coefficient of Performance

Heating water	Cooling water inlet temp.°C		
	28	30	32
90	0.319	0.304	0.290
85	0.339	0.321	0.301
80	0.319	0.298	0.275
75	0.290	–	–
70	0.291	–	–

If the experimental modifications and the drawbacks caused by manufacture are improved, at the work condition of 85°C of heating water inlet and 28C of cooling water inlet, a cooling capacity of 995 W and a COP of 0.477 can be got. If the work condition of 85°C of heating water inlet and 30°C of cooling water inlet is considered, a cooling capacity of 907 W and COP of 0.446 can be expected.

THE USE OF SPLIT HEAT PIPES TO HEAT OR COOL ADSORBER FOR ICE MAKING IN FISHING BOAT

The third example is the use of split heat pipes to heat or cool adsorber for ice making in fishing boat. The application of these technologies avoid the corrosion of adsorber at the heating phase by exhausted gases and at the cooling phase by seawater, and also has the advantage of high heat transfer performance. With such arrangement and careful considerations of the arrangement of wicks in heat pipes, and also the use of compound adsorbent (calcium chrolide and activated carbon)-amminia adsorption pair [14], the system test has shown the specific refrigeration power for more than 365 W/kg at –15°C. Fig. 10 shows the adsorption/desorption performances of the compound adsorbent-ammonia, which has been applied in experimental systems.

For the adsorption ice maker on fishing boats that use chemical adsorbent-ammonia as working pair, one performance limit is that the steel adsorber cannot withstand sea water cooling, though copper is good for sea water cooling but it is corrosive with ammonia. Traditional method to solve this problem is to use fresh water to cool adsorber with heat output to sea water via pumping through a second heat exchanger, this method will increase the power consumption. In order to solve this problem, a heat pipe type adsorption system to perform the cooling and heating process for adsorber without pumping was proposed [15].

The second performance limit for the adsorption ice maker on fishing boats is the specific cooling power. The space on the deck is limited, the improvement of the specific cooling power could make the system more compact. For this problem, the compound adsorbent to improve the cooling power per volume has been successfully demonstrated [16].

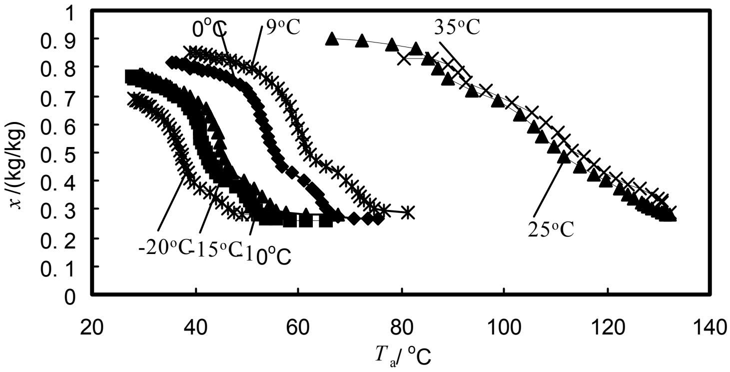
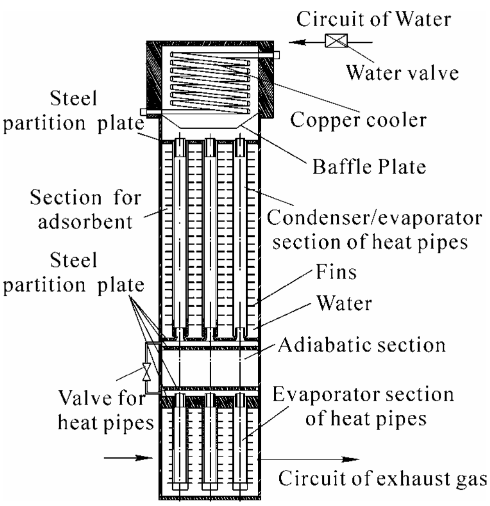


Fig. 10. Adsorption and desorption isobars for compound adsorbent-ammonia

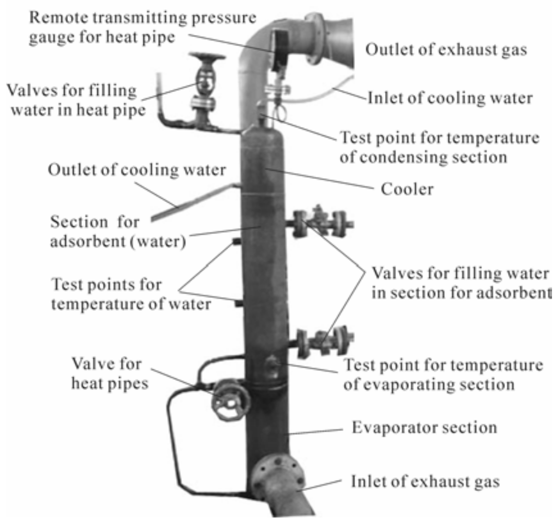
Thermosyphon heat pipe type adsorber for fishing boats

The first scheme for the adsorption ice maker on fishing boats proposed is the thermosiphon heat pipe type adsorber, which is shown in Fig.11. The heating and cooling phase of this adsorber is performed by the thermosyphon principle. The working media in heat pipe is water.

At the heating process, the valve for heat pipes is open and the water valve is closed, the water in the evaporator section of heat pipes is heated by the high temperature exhausted gases (from diesel engine for example), which is simulated by the oil burner, and then the vapour condenses inside fin tubes in the section for adsorbent, which will supply the heat flux for desorption. At the cooling phase for adsorbent, the valve for heat pipes is closed and the water valve is open, the water in the heat pipes in adsorbent part evaporates and equivalents the adsorption heat, then the vapour condenses in the copper coil cooler. The water is filled in the section for adsorbent to measure the heat transfer performance of heat pipes.



a)



b)

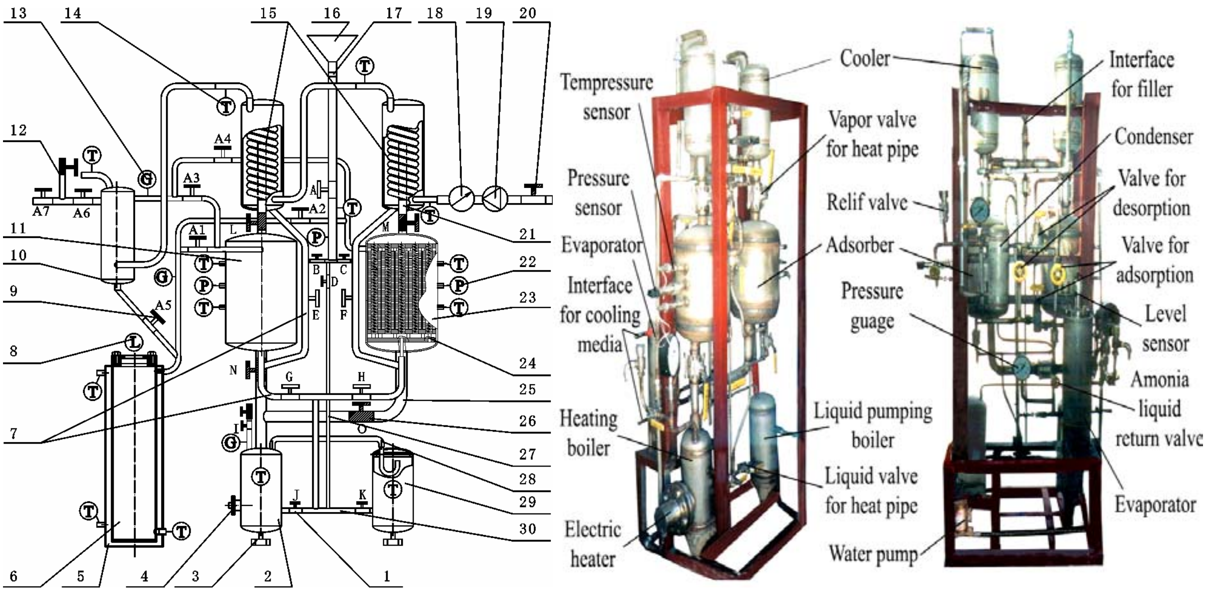
Fig. 11. Thermosyphon adsorber: a) Construction of system; b) Photo of adsorption test unit

The required heating/cooling power transferred by one heat pipe for adsorbent in adsorber is 556 W when the lowest adsorbing temperature, the highest desorbing temperature, the evaporating temperature and the cycle time are respectively 47 °C, 130 °C, –15 °C and 10 min. The heat transfer performance of one heat pipe is simulated, the average heating/cooling power for desorption/adsorption are respectively 571 W/643 W, which could meet the heating/cooling demands of adsorbent for adsorption/desorption at the cycle time of 10 min. A test unit shown as Fig. 11 (b) is set up to test the heating/cooling performance of heat pipe type adsorber, and experiments of the test unit are in good agreement to the simulation. The performance of two-bed adsorption system (each contains 29 kg compound adsorbent) is predicted, the cooling power of two-bed system, which use separated heat pipe adsorbers, is about 17.8 kW with mass recovery between two beds at the evaporating temperature of –15 °C.

But there is one limit for the thermosyphon heat pipe type adsorber. The copper cooler is also heated by the evaporating part of heat pipe at the heating phase of adsorbent part, and then the salt will be out of seawater and stick on the copper cooler, which will influence the heat transfer performance. In order to solve this problem, a split heat pipe type compound adsorption ice making unit is designed and constructed.

Split heat pipe type compound adsorption ice making unit for fishing boats

The system design and the photo of the compound adsorbent-ammonia adsorption refrigeration system are shown in Fig. 12. The main components in the split heat pipe type adsorption system are heating boiler, liquid pumping boiler, adsorbers, coolers, condenser and evaporator. The compound adsorbent are used in adsorber, each adsorber contains 1.88 kg adsorbent, and the inside fined tubes inside adsorber serves as the heat pipe part. The vapor channel/liquid return pipes inside adsorber serves as vapor channel at heating phase, and serves as liquid return pipes for liquid pumping phase.



a) b)

Fig. 12. Split heat pipe type compound adsorption refrigeration system with liquid pumping function: a) structure of the setup; b) the system outlook: 1 – Liquid valve for heat pipe; 2 – Heating boiler; 3 – Liquid tap interface; 4 – Electric heater; 5 – Glycol jacket; 6 – Evaporator; 7 – Liquid tube for heat pipe; 8 – Megneto strictive level sensor; 9 – Ammonia valve; 10 – Condenser; 11 – Adsorebr 1; 12 – Relief valve; 13 – Pressure gauge; 14 – Temperature senser; 15 – Coil pipe cooler; 16 – Filler; 17 – Screw interface; 18 – Flow sensor; 19 – Water pump; 20 – Water valve; 21 – Vapor channel for heat pipe for cooling phase; 22 – Pressure sensor; 23 – Adsorber 2; 24 – Vapor channel/Liquid return pipe inside adsorber; 25 – Vapor channel for heat pipe; 26 – Vapor valve for heat pipe; 27 – Pumping tube; 28 – Pressure equivalent pipe for boilers; 29 – Liquid pumping boiler; 30 – Liquid equivalent pipe for boilers

The liquid in heating boiler is heated by electric heater, which simulates the waste heat recovery process. For the heating and desorption phase of adsorber, the vapor evaporates in boiler at the heating effect of electric heater, and condenses inside the fined tubes in adsorber, which provides the desorption heat for compound adsorbent. At the initial phase for the cooling and adsorption, the adsorber is in connection with the water cooler, which is cooled by the seawater in coil condenser, and the liquid in the liquid pump boiler is pumped up by pump pipe under the pressure head between liquid pump boiler and inside pipe in adsorber, and then the redundant liquid will return to heating boiler through liquid return pipe. And then the liquid pump boiler will be disconnected with adsorber, and the liquid inside fined tubes in adsorber evaporates to the cooler, which takes the adsorption heat out of adsorber, and condenses in cooler, go back to adsorber by the liquid channel for heat pipe for cooling phase.

The liquid return channel in adsorber also serves as vapor channel for heat pipe for heating phase; it is designed inside the adsorber to decrease the heat loss of heating boiler. The vapor channel for heat pipe for cooling phase is also designed inside cooler, the advantage of such design can make the system simplified, and it can also decrease the flow resistance of vapor that evaporates at low pressure because there are no elbows in the vapor channel. The liquid inside boilers are filled by the filler. The refrigerant ammonia desorbed from adsorber is condensed in condenser, and the ammonia liquid in evaporator may provide evaporation for adsorption. The adsorption quantity is measured by the magneto strictive level sensor, whose relative error is only 0.05 %. The evaporating temperature is controlled by the glycol which cycled inside a low temperature thermostat. City water (with temperature controlled) is used to supply cooling for the cooper coil condenser, which provides the cooling to release heat from adsorbent bed.

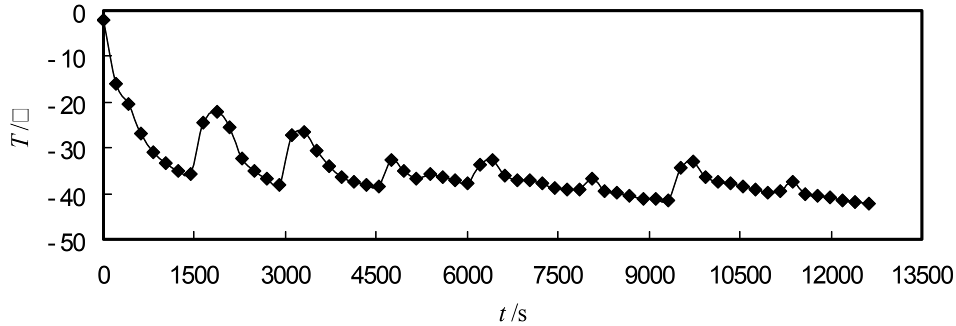
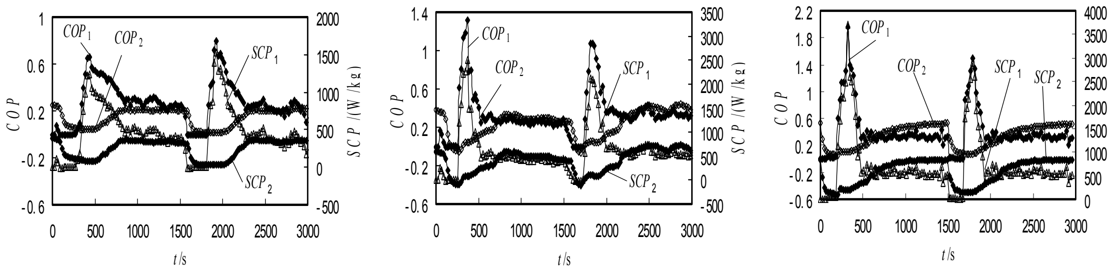


Fig. 13. The lowest evaporating temperature test

The temperature of cooling water is controlled at 25 °C, if the glycol doesn't circulate inside the thermostat jacket, the lowest evaporating temperature reached is measured, the results are shown in Fig. 13. It is seen that the lowest evaporating temperature is as low as –42 °C after continuously refrigeration for 3.6 h.



a) b) c)

Fig. 14. Performance under different evaporating temperature: a) -35°C; b) -25°C, c) -15°C

There are two methods to calculate the cooling power of split heat pipe adsorption test unit, one is to calculate the cooling power by the measured magneto stcitive liquid level sensor, and the latent heat of the cycled ammonia corresponds cooling effect, the cooling power is then obtained by dividing the refrigeration effect with cycle time, which is named as $W_{L1,}$ the specific cooling power SCP and COP are named as SCP_1 and COP_1respectively. Another method is the use of the cycled glycol to test the cooling power (temperature difference and mass flow rate measurements), the corresponding performances are named as W_{L2}, SCP_2 and COP_2 respectively.

The performance of this test unit is tested, and the results of COP and SCP under the evaporating temperature of –35 °C, –25 °C and –15 °C are shown in Fig. 14.

When the evaporating temperature is controlled at –35 °C (Fig. 14, a), the average cooling power of W_{L1} is 0.89 kW, and the average cooling power of W_{L2} is 0.57 kW. The average value of W_{L2} is lower than that of W_{L1} for the reason of cooling power losses. The average value of COP_1 and average value of SCP_1 are 0.27 and 476.8 W/kg respectively, while the average value of COP_2 is 0.18, and average value of SCP_2 is 302.8 W/kg.

When the evaporating temperature is controlled at –25 °C, the average cooling power of W_{L1} is 1.14 kW, and the average cooling power of W_{L2} is 0.92 kW. COP_1, COP_2 and SCP_1 and SCP_2 are shown in Fig. 14, b. The average value of COP_1 and average value of SCP_1 are 0.34 and 605.2 W/kg respectively, while the average value of COP_2 is 0.28, and average value of SCP_2 is 487.0 W/kg.

When the lowest evaporating temperature is controlled at about –15 °C, the average cooling power of W_{L1} is 1.37 kW, and the average cooling power of W_{L2} is 1.23kW. The measured COP_1, COP_2 and SCP_1 and SCP_2 are shown in Fig. 14, c. The average value of COP_1 and average value of SCP_1 are respectively as high as 0.41 and 731.0 W/kg, which is 2.5 times and 22.2 times of the results of activated carbon-methanol adsorption ice maker [10], while the average value of COP_2 is 0.38, and average value of SCP_2 is 652.2 W/kg.

The difference between W_{L1} and W_{L2} decreases with the increases of evaporating temperature. It is resulted by the cooling power losses, if the refrigeration temperature is increased, the measured differences between the two methods will turn to small.

The heat transfer performance of this test unit is tested, and the heat transfer coefficient for heating and cooling phases are shown in Fig. 15. The average heat transfer coefficient for heating and cooling phases are 152.3 $Wm^{-2o}C^{-1}$ and 159.4 $Wm^{-2o}C^{-1}$ respectively, which is improved 77% in comparison with the results of activated carbon-methanol adsorption ice maker [10].

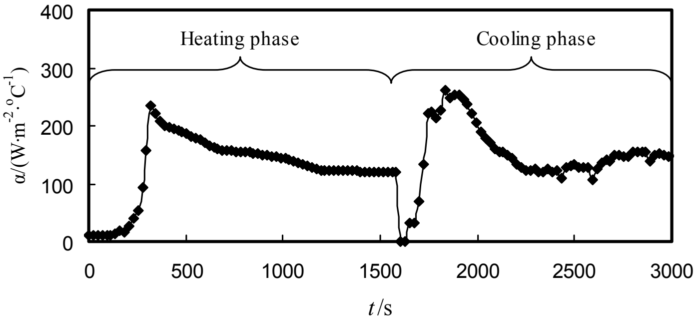


Fig. 15. Heat transfer coefficient at heating and cooling phase

CONCLUSIONS

Adsorption refrigeration systems integrated with heat pipes are quite efficient for real applications. The research work has proved that heat pipes could be used as heat exchanger for adsorbers, evaporators or condensers. The proper design may help to simplify adsorption refrigeration system, make the system cost lower, and solve the problems of corrosions etc.

Based upon various types of heat pipe design, adsorption water chiller, adsorption room air conditioner, and adsorption ice maker for fishing boat have been successfully demonstrated. Some of adsorption refrigeration systems have been even commercialized.

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