Adsorption 9: 349–358, 2003

Experimental Results and Analysis for Adsorption Ice-Making System with Consolidated Adsorbent

S.G. WANG, R.Z. WANG*, J.Y. WU AND Y.X. XU
Institute of Refrigeration & Cryogenics, Shanghai Jiao Tong University, Shanghai 200030, China

Received July 17, 2002; Revised March 28, 2003; Accepted May 12, 2003

Abstract. An adsorption ice-making machine has been built with a single consolidated adsorber and activated carbon-methanol pair. A consolidated adsorbent block made of activated carbon mixed with a binder with good heat transfer properties has been developed and implemented in the adsorber. The design is focused on the adsorber consisting of copper finned tubes and carbon blocks. Experimental tests have been performed suitable for ice making. This paper describes the experimental results of such an ice-maker operating with an intermittent cycle and a cycle time of 35 minutes. The thermal conditions used to test the cycle are: 115°C heat source, 22°C heat sink, the evaporator temperature corresponding to the chilled ethylene glycol temperature is −7°C. At this evaporating pressure, the mass transfer resistance controls the adsorption process. Test results show that the COP reaches 0.07 whereas the SCP (specific cooling power) is 11 W kg^{-1} activated carbon. A two-bed adsorptive prototype ice-making machine operating with a heat and mass recovery cycle has also been made for onboard adsorption refrigeration in fishing boats. Good performances have been achieved due to improved mass transfer and the new ice maker can produce 18–20 kg h^{-1} of flake ice at mean temperature of −7°C.

Keywords: adsorption, consolidated block, activated carbon, ice-maker

Introduction

Adsorption systems are directly heat-powered, especially operated by waste heat or renewable energy, so they can greatly contribute to reduce primary energy consumption and environmental pollution. It seems possible to link adsorption systems to waste heat recovery from diesel engines in fishing boats. Fishing boats traditionally used crushed ice for caught fish preservation. Nowadays larger boats use mechanical refrigeration to keep the ice from melting. But, fishing boats with tonnage below 100 tons cannot carry compressor-icemaker onboard, because of their small horsepower. Therefore, fishermen have to take a lot of ice to keep their catches fresh when they go fishing on the sea. Fishing boat icemaker powered by exhausted heat of diesel engine can properly solve that problem, and there is no any increase consumption of oil.

Fernandez-Seara et al. (1998) reported the design, modeling and parametric analysis of a gas-to-thermal fluid heat recovery system from engine exhausts in a trawler chiller fishing boat to power an NH_3-H_2O absorption refrigeration plant for onboard cooling production. Results obtained from simulations of the system and the design of a practical application from real data show the feasibility of employing this type of heat recovery system in the case studied. Zhu et al. (1992) described a zeolite-water adsorption refrigeration system to produce chilled water for preserving aquatic products on a fishing boat, in which the exhausted gas from a diesel engine is utilized as a heat source. Hunan DY Refrigeration Co. (2000) reported DY fishing boat diesel engine exhausted icemaker, which includes one icemaker, one condenser and one DY generator system (one DY generator system contains one chemical

*To whom correspondence should be addressed.

reactor, one ammonia tank, one refrigeration control equipment et al.). These researches are mainly under simulation and experiment.

Vasiliev et al. (1992) showed the application of the adsorption pair activated carbon fiber material- acetone for the refrigerator with a chamber volume of 120 dm^3 and with the time of the adsorption- regeneration cycle of 2 hours. Their trials were performed at room temperature for maintaining the mean air temperature in the refrigerator chamber not higher than $+5°C$ and not for ice making. Several adsorption refrigeration prototypes have been developed and tested in our laboratory, typical examples are continuous heat regenerative adsorption ice maker using spiral plate adsorbers, solar powered adsorption ice maker, waste heat driven air conditioning system for automobiles (Wang, 2001a). Recently a new experimental setup designed for the use in fishing boats has also been built in order to test the predicted capacity of ice making.

An adsorption refrigerator to produce ice is mainly reported among the adsorptive solar cooling systems with day/night cycle (Worsoe-Schmidt, 1983; Pons et al., 1986; Boubakri et al., 1992). To make this unit economically viable, its size, linked to the cost, must be reduced. One of the ways solving these problems is the increase in the density and thermal conductivity of the solid adsorbent as is developed by Tamainot-Telto and Critoph (1997). They have used monolithic carbon, based on 208C precursor mixed with an organic binder, compressed and fired. In addition, because of the large quantities of refrigerant and adsorbent required we have to use consolidated blocks. This paper presents the design, test and analysis of this ice-maker with a consolidated adsorber and activated carbon-methanol pair powered by waste heat.

Fishing boats never stop their main engine when cruising or fishing. The exhausted gases outlet temperature may reach around 400°C. Because methanol could in any case decompose at temperatures much in excess of 120°C, gas-fluid heat exchangers (HXs) is needed. Besides, onboard adsorption refrigeration systems can profit from using the inexpensive sea water as cooling medium in the adsorber and condenser which allows one to maintain low adsorption and condensation temperatures.

Consolidated Blocks

Among the three components (adsorber, evaporator and condenser) used in adsorption systems, only the adsorber is specific. The recognized drawback of solid-gas adsorbers is mainly the poor heat transfer. The heat and mass transfers have very important roles and their optimization is one of the technological challenges to be taken up in order to develop these systems (Meunier, 1998).

Generally the overall conductivity of a granular adsorber is low, in which its heat transfer is poor. To intensify heat transfer in adsorbers for getting higher performances, One method is to produce a solid adsorbent shape and to build consolidated adsorbers, which they may also increase the overall power density for the machine and come with an increase in compactness. Problems of cracking and warping in solid blocks during activation were avoided by making the blocks in five or six segments and then bonding them together after activation.

The used coconut-based activated carbon (AC) marketed by the JVHQ Co. (China) is in the form of the size of 14–28 meshes and the bulk density of about 450 kg m^{-3}.

The form of AC blocks proposed is as Fig. 1. It was produced at our laboratory from the granular AC. Its manufacturing procedure is as follows: the AC grains were mixed together with pitch binder and water in the proper ratio, then molded by compression at some tens of MPa. Finally, the block is heated at 120°C for 3 hours after it is withdrawn from the mould. After activation it is achieved by bonding the block onto a rectangular fin easily processed of the same size. The final produce is in the form of a cuboid with $280 \times 210 \times 11$ mm^3. The mass of the sample is 0.275 kg. The bulk density of the block is 551 kg m^{-3}.

In this way heat is transferred quickly along the copper fin and from there axially into the charcoal, thus the

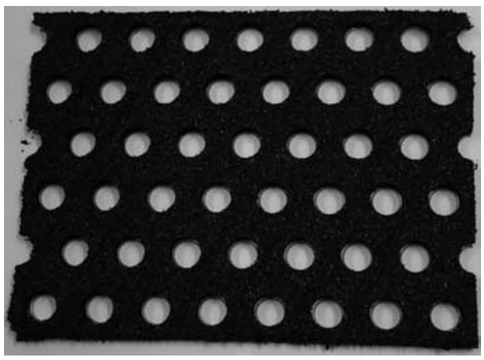

Figure 1. Photograph of the consolidated AC block.

heat transfer does not rely solely on radial conduction through the charcoal.

With improvement of the heat transfer, the compression of the AC results in an increased resistance to mass transfer which is a negative effect on the process (Guilleminot et al., 1993; Poyelle et al., 1996; Eun et al., 2000). Gas flow channels have, in general, to be introduced on the double surface of the block to get reasonably high permeability compatible with the high heat rates expected. Arteries with half cylinders of 3 mm-diameter have been designed between two holes of the same row on each side of the block.

The thermal conductivity of the blocks is determined by a fast simple method of measurement developed by Liu et al. (1990). The maximum cumulative errors of the measured results are estimated to be within 8%. Although the samples are degassed before use, the thermal conductivity test has to be carried out at ambient conditions and in air. The thermal conductivity of the blocks ranges from 0.27 to 0.34 W m^{-1} K^{-1} at ambient temperature 22°C without preliminary preparation of the sample surface. It is about three times higher than that of ordinary granular material (0.11 W m^{-1} K^{-1}) because of the absence of large voids and the existence of an unbroken conduction path.

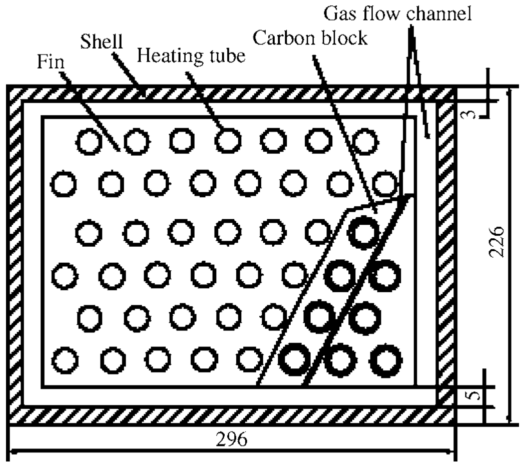

Figure 2. Cross section of adsorber.

Consolidated Adsorber

One useful method of increasing the bed conductivity is to insert metal fins between the blocks, then, the charcoal would adhere to the metal surface, thus reducing the conduction path length. Based on the experimental data and numerical analysis, Babenko et al. (1998) recommended the copper fins with the half-thickness from 0.1 up to 0.4 mm, fin spacing less than 10 mm, and fin height less than 20 mm. Poyelle et al. (1996) gave the optimum bed thickness 15 mm without fins and adapted to her geometry based on the cooling rate in the case of a cylindrical adsorber heated at the inner side. The fins are 0.2 mm thick and spaced 11 mm apart in our adsorber between which are placed those blocks. After the pipes are expanded in the bed, the difference in the thermal expansion coefficient of the two materials may not lead to problems of separation along the bond or cracking of the charcoal brick. A good thermal bond can be achieved. Figure 2 displays a scheme of cross section of the adsorber.

An adsorber configuration consists of tubular HXs with fins in the shape of cuboids, as shown in Fig. 3. The carbon blocks are distributed in five components partitioned by supporting plate with vapor flow gaps. There is spacing of about 5 mm between the bed shell and the core (four sides of the blocks) enwrapped with stainless steel screen and wire netting. The heat transfer fluid flows inside the tubes and adsorbent blocks are arranged between the fins. Cross-braces are welded on the external surface of the adsorber to keep in the existing shape under low operating pressure. The adsorber contains 41 kg of AC. The net volume (adsorbent plus fins and tubes) is 0.116 m^3. The heat exchanger area on fin side is 12.3 m^2. The overall heat transfer coefficient of 95 W m^{-2} K^{-1} between the heat transfer fluid and the adsorber and the wall heat transfer coefficient of 252 W m^{-2} K^{-1} between block and fin are estimated according to the relation given by Meunier (1998). The wall heat transfer coefficient is higher than the heat transfer coefficient of 180 W m^{-2} K^{-1} reported by Guilleminot et al. (1993) between the external wall of the measurement cell and the consolidated composite made of zeolite and metallic foam without preliminary preparation of the sample surface.

The temperature-time profiles at six points within the bed are measured by copper-constantan thermocouples. A pressure transducer is used to measure the adsorbate vapor pressure inside the bed.

Description of the Experimental Setup

Figure 4 shows a scheme of the experimental setup that has been built. The system is composed of one adsorber, an evaporator, a condenser, a heat source and a heat sink.

Figure 3. Photograph of the consolidated adsorber.

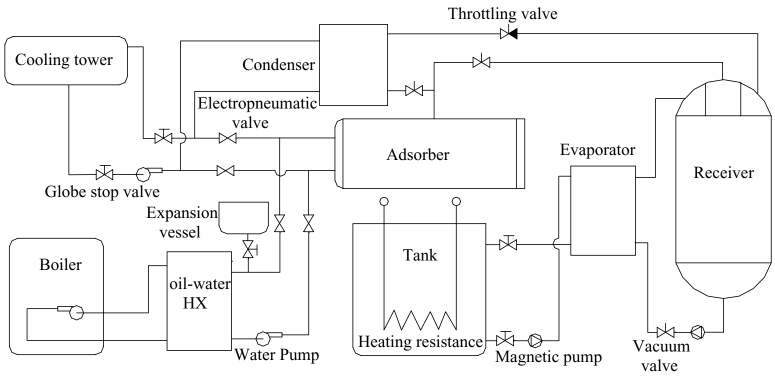

Figure 4. Experimental setup of a single-adsorber ice-making system.

The evaporator with 0.86 m^2 of heat exchanger area and the condenser with 1.47 m^2 are liquid/liquid plate HXs. At the condenser bottom, a receiver with 0.025 m^3 of volume collects and measures the condensed refrigerant. A magnetic pump is used to circulate the chilled methanol refrigerant from the bottom of the receiver to one inlet of the evaporator (cooling output heat exchanger).

In an adsorption system, alternative heating and cooling of the adsorber is necessary, and a single liquid-phase fluid is used as the thermal fluid. A low fluid viscosity is required at low temperature (around 40°C) to achieve a heat transfer coefficient up to 1000 W m^{-2} K^{-1}. Furthermore, the heating fluid saturation pressure at high temperature must not be too large (Guilleminot et al., 1998). In this study water is chosen as the heat transfer fluid.

Heat-conducting oil boiler with electric heating (power rating 44 kW) releases heat through heat-conducting oil thermal fluid. An oil-water HX links this primary circuit to the secondary one during the heating phase of the cycle. The hot water circuit has a pressure gauge and a pressure release valve to relieve any excessive pressure. This heat source can be replaced by a diesel engine in the case of a waste heat driven unit.

Cooling water is used as the heat sink and maintains a low operating temperature in a closed-loop circuit. The system provides simultaneous cooling to two regulated circuits. One circuit is directly connected to the condenser. The second circuit controlled by pneumatic valves is connected to the adsorber during the cooling period of the cycle. In the system there is one pump. The heat sink is a water cooling tower on the rooftop of our laboratory.

An auxiliary chilled-ethylene glycol source is used and provides heat to a methanol loop in order to balance the cooling load in the evaporator heat exchanger.

By means of the test facility, complete cycles of the machine can be carried on, monitoring almost all components by a computer. A data acquisition system makes it possible to read all the data from the document data files stored in the computer. In particular, the following parameters can be measured by the test facility:

- temperatures at six points of the adsorber;
- inlet and outlet temperatures of the water flowing into the adsorber;
- inlet and outlet temperatures of the cooling water flowing into the condenser;
- inlet and outlet temperatures of the water flowing into the oil-water HX;

– inlet and outlet temperatures of the ethylene glycol flowing into the evaporator heat exchanger;
– temperatures of the methanol receiver and ethylene glycol tank;
– heating and cooling water-flowrate;
– ethylene glycol-flowrate;
– pressure in adsorber, condenser and methanol receiver.

Using the test device, numerous tests have been carried out in order to calculate the COP and the specific cooling power (SCP).

The Principle of a Single-Adsorber Cooling System

In a Clapeyron diagram (ln p vs. $-1/T$), the intermittent cycle is presented as follows (see Fig. 5):

At the beginning of the cycle, the temperature of the adsorber is at the lowest temperature of the cycle T_{a2} (point 1) and the pressure in it is the pressure of the evaporator. The adsorber is heated, until its pressure reaches the condensing pressure constrained by the cooling water temperature (point 2). At this point, the check valve between adsorber and condenser is opened, then condensation starts, where the condenser is connected to a glass receiver. At the end of this phase (point 3), the valve between the adsorber and condenser is closed and cooling phase starts. The pressure in the adsorber decreases until it reaches the evaporating pressure constrained by the low-temperature heat source (point 4). At this point, the valve between the adsorber and evaporator is opened, then evaporation starts. It is closed when the temperature reaches the starting point. The heat input to the adsorber is Q_{hr}. The heat input to the evaporator is Q_{ev}.

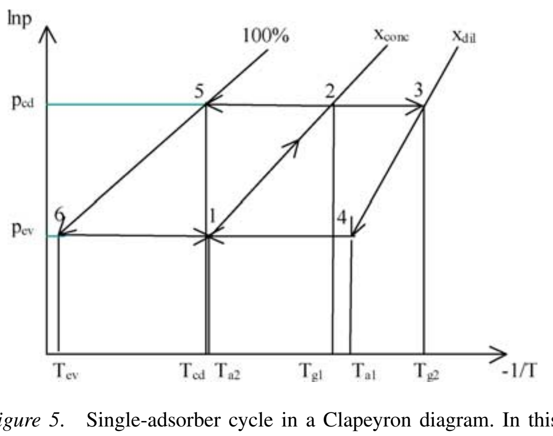

Figure 5. Single-adsorber cycle in a Clapeyron diagram. In this diagram T_{a2} represents the temperature at the end of adsorption; T_{a1} is the temperature at start of adsorption; T_{g1} is temperature at start of regeneration; and T_{g2} represents the temperature at the end of desorption process.

The performance of a cooling cycle is characterized mainly by two parameters:

$$\mathrm{COP} = Q_{ev}/Q_{hr} \tag{1}$$

$$\mathrm{SCP} = Q_{ev}/(M_c \tau_{cyc}) \tag{2}$$

where M_c is the total mass of the adsorbent (kg), τ_{cyc} is the cycle time (s). The COP measures the ratio of the energy Q_{ev} (kJ) available at the evaporator to the energy Q_{hr} (kJ) supplied to adsorbers by the external boiler. The SCP [W kg^{-1}] measures the cooling power during a cycle on the basis of the unit mass of the adsorbent.

Experimental Results and Discussion

The experiments suitable for an ice-making system have been done at specific operating conditions. The cooling water temperature (T_c) is 22°C and the evaporator temperature corresponds to the chilled ethylene glycol temperature of $T_0 = -7$°C. The hot water temperature (T_h) supplied ranges from 110°C to 125°C, which allows a maximum generating temperature (T_{g2}) approximately between 105°C and 120°C. Following initial experiments, the cycling time chosen was 35 minutes. It allows a heating and desorption time of 15 minutes which corresponds to the optimum heat input for maximum cooling power. For the complete cycle, the cooling load supply in the evaporator is over when the temperature in the receiver approaches −9°C around. Therefore, in the next desorption phase the glycol circuit is operated continuously for some minutes in order to measure the cooling load completely.

One of the most interesting results is the real cycle figure drawing in a Clapeyron diagram for the single consolidated adsorber system. In fact it allows us to make a better control of each phase of the cycle. Plotting the pressure in the adsorber as a function of its average temperature for $T_h = 115$°C and the other parameters fixed (Fig. 6), the result corresponds to the ideal cycle displayed in Fig. 5. The pressure level for isobaric adsorption and desorption is fixed by the evaporator and condenser temperature, whereas the isosteric heating and cooling is fixed by the temperature in the adsorber. The heating and the cooling phases obtained experimentally are close to the theoretical isosteres. During adsorption and desorption it is very difficult

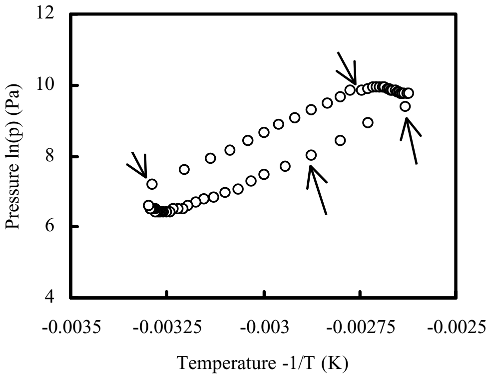

Figure 6. Real cycle measured in the Clapeyron diagram.

to have a constant pressure because of the complex heat and mass transfer process as well as their irreversibility. Since only one adsorber is involved in this machine, the cooling power is intermittently produced for the adsorption phase. Heat leakage in the methanol receiver makes its pressure increase for non-adsorption time so that the bed pressure may reach the methanol vapor pressure early, as shown in Fig. 6. Subsequently, adsorption proceeds with decreasing pressure and, because the methanol is evaporating, the temperature of the receiver decreases down to below $-7°C$. From this moment to the end of the adsorption period, the pressure is always much lower than the saturation pressure of methanol at point 1. The decrease in bed average temperature is also somewhat slower than before. These could be correlated with the mass transfer of the adsorber and with the fact that the energy for freezing ethylene glycol is now involved in the heat balance of the evaporator.

The pressure drop between the vapor in the adsorber and the condensing pressure is less than that between the evaporating pressure and the vapor in the adsorber (see Figs. 7 and 8). It can be explained by the too large resistance to mass transfer of the adsorbent blocks at

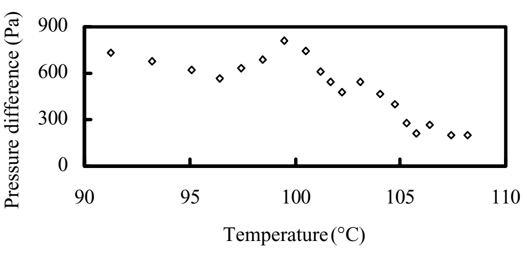

Figure 7. The pressure drop between the vapor in the adsorber and the condensing pressure.

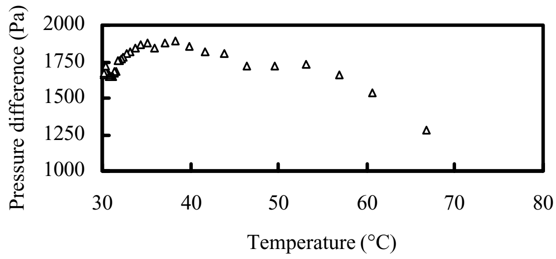

Figure 8. The pressure drop between the evaporating pressure and the vapor in the adsorber.

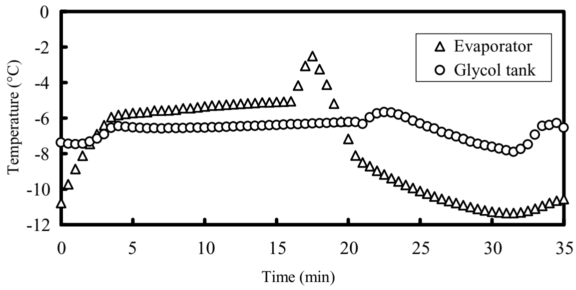

Figure 9. The temperature evolution of evaporation and that in the glycol tank.

this low evaporating pressure level. The mass transfer properties are not good mainly because of deterioration of the arteries during assembling. In contrast, at the high condensing pressure that should be up to 5 kPa reported by Guilleminot et al. (1998), the small pressure drop shows that the permeability of the adsorbent blocks is sufficient.

Figure 9 presents the temperature variation of evaporation and the average temperature evolution in the ethylene glycol tank during one cycle. At the beginning of the cooling period, two magnetic pumps begin to work so that the temperature in the receiver suddenly goes up due to mixing of the liquid. After adsorption the temperatures of both evaporation liquid and ethylene glycol decrease. The average temperature in the ethylene glycol tank is able to keep around $-7°C$ through heat balance provided automatically by electric heater during adsorption phase during 17–35 minutes period. The average difference between the two temperatures is about 3.7°C.

Many tests have been done with mainly changes of the temperature levels of the heating fluid in order to obtain the maximum fluid temperature level that could be heated by the exhausted gas of the diesel engine when the ice-making system is used on fishing boats. For

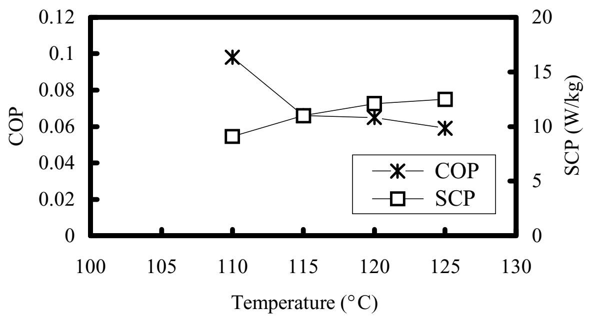

Figure 10. Performance variation with heat transfer fluid temperature.

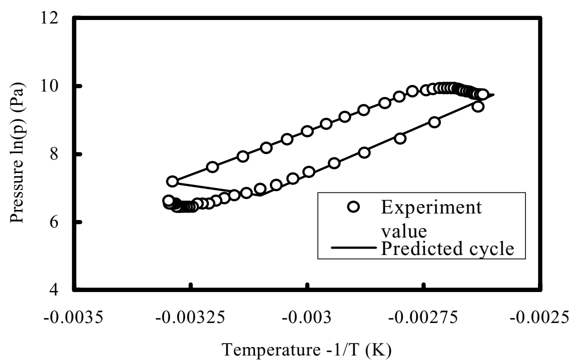

Figure 11. Real cycle and improved cycle with the same source operating temperatures.

each test, the COP and SCP are reported as can be seen in Fig. 10. In this figure, the temperature presented on the x-axis is the temperature of the heat transfer fluid. The SCP increases with heating fluid temperature to asymptotic value reached above 125°C. On the other hand, the COP decreases with heating fluid temperature. Because methanol could in any case decompose at temperatures much in excess of 120°C and our objective to be reached is a high SCP, the temperature of heating fluid ranging from 115°C to 120°C is proper for these operating tests of our experimental setup. The results of this system show that, for example, a SCP of 11 W kg^{-1} AC and a COP of 0.07 have been achieved to produce 0.45 kW of cooling at temperature −7°C of the chilled ethylene glycol.

Performance with Improved Mass Transfer Properties

The too-low permeability of the adsorbent blocks resulted for the larger pressure drop measured between the evaporating pressure and the vapor in the adsorber at this pressure level (Fig. 8). This permeability of order of below 10^{-13} m^2 can be estimated while the permeability of a granular fixed adsorber is about 10^{-9} m^2 (Guilleminot et al., 1993). A twentyfold improvement (order of 10^{-11} m^2 or higher) in permeability could be sufficient for a good operation (Guilleminot et al., 1998; Gurgel et al., 2001). Figure 11 shows the effect of the improved mass transfer in the adsorber on the evolution of an intermittent cycle in a Clapeyron diagram. At the last period of evaporating phase, the pressure in the adsorber for the measured cycle remains lower than the imposed evaporating pressure, and therefore, the cycled mass is lower than expected. Because the mass transfer resistance controls the process at this low evaporating temperature, the pressure difference between the evaporating pressure and adsorption pressure will be smaller after the mass transfer is improved. The cooling and adsorption time would be reduced from 20 minutes to 15 minutes or less and the cycled mass of methanol would become larger. Therefore the SCP could be predicted to achieve the value of 25 W kg^{-1} with these new blocks.

The vapor pressure in the adsorber is very sensitive to the mass transfer properties for low operating pressure systems in the case of using refrigerants like water or methanol (Fig. 11). During the evaporating-adsorption process the small pressure drop between the evaporating pressure and the vapor in the adsorber can be essential to the cycle performance. As a result, gas flow channels in the adsorber to get reasonably mass transfer resistance would be important in designing of the adsorber.

Ice Maker with Adsorbent Blocks of Improved Mass Transfer Properties

Figure 12 shows a picture of the adsorption ice maker prototype that has been built recently. The main components are two adsorbers, a condenser, a receiver, a gas-water heat exchanger (G/W HX), a hot-water storage tank and a flake ice maker (the COLDISC ice maker made by North Star Ice Equipment Co.). The water in the hot-water tank, which is heated by the fume gas from the burner through the G/W HX, can reach the temperature between 100°C and 120°C. To test accurately the cooling load this flake ice maker is replaced later by an auxiliary chilled-ethylene glycol source which provides heating through electric heater to a methanol loop in order to balance the cooling load in the evaporator.

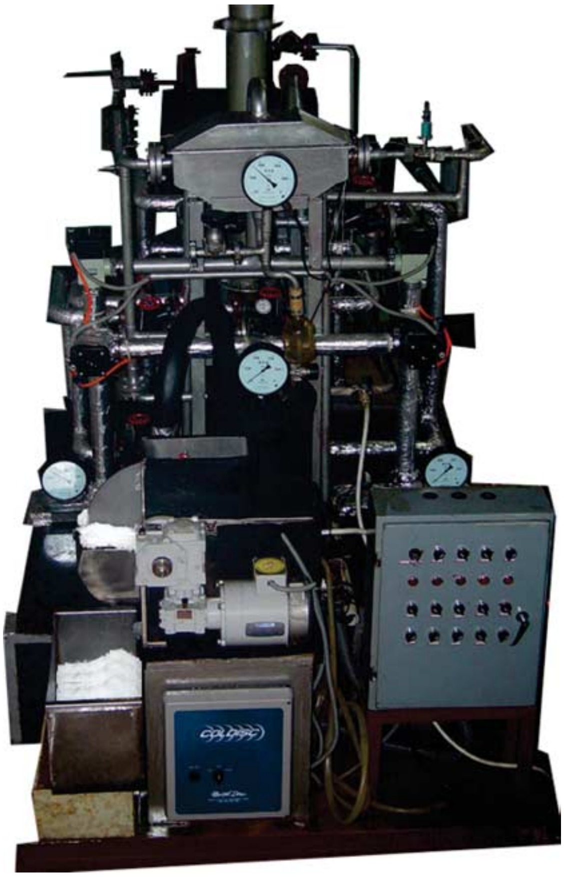

Figure 12. A new adsorption ice-maker prototype.

The adsorber consists of three parts of carbon blocks, which the cross section is shown in Fig. 13. The bulk density of the block is 600 kg m^{-3}. Arteries in the form of half cylinders with diameter of 4 mm have been developed between two holes of the same row on each side of the block. Each part is enwrapped with stainless wire netting. The adsorber in the shape of cuboids contains about 56 kg of activated carbon blocks. The volume inside the adsorber (the core plus free space) is 0.148 m^3.

The experiments were run on the adsorptive ice-maker with heat and mass recovery process (HMR process). The description of adsorption cycle with a HMR cycle could be found in Wang (2001b). The cooling water temperature is 24.5°C around. The hot water temperature supplied ranges 100°C to 120°C. The cycling time chosen was 40 minutes. It allows a heating and desorption time of 20 minutes including heat recovery time of 1.5 minutes and mass recovery time of 1 minute. Test results of this ice maker show that flake ice of 18–20 kg h^{-1} is produced.

After the flake ice maker is replaced by an auxiliary chilled-ethylene glycol source, experiments were carried out. Thus, we can get performances of the prototype corresponding to different evaporating temperatures. Cooling power is obtained experimentally by direct measurements of the chilled-ethylene glycol flowrates and the temperature differences between outlet and inlet of the fluid. Here, the cooling water

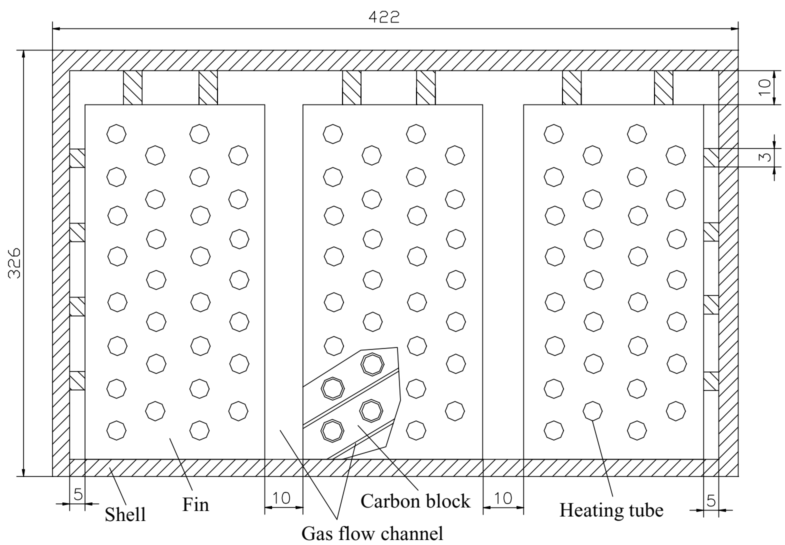

Figure 13. Cross section of the adsorber.

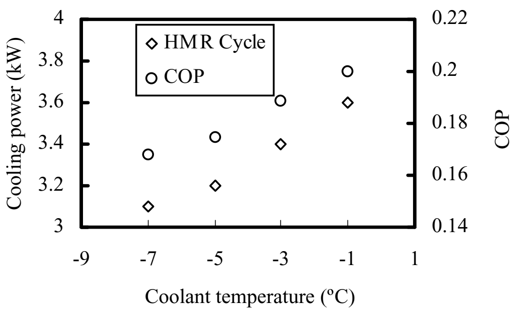

Figure 14. Performance variation with the temperature in the ethylene glycol tank.

temperature during tests was 11°C around. The other conditions are the same as the above paragraph.

The COP and the cooling power increase strongly with the average temperature in the ethylene glycol tank, as shown in Fig. 14. The average cooling power reaches experimentally 3.3 kW, and a mean COP of 0.183 and a mean SCP of 30 W kg^{-1} carbon have been achieved when the ethylene glycol temperature is controlled from -7 to -1°C.

Conclusions

A single-bed adsorption cooling system has been built and tested with consolidated adsorbent and activated carbon-methanol pair. The obtained experimental results are very interesting in designing a new prototype. A highly conductive adsorbent block with good heat transfer has been developed. A limitation to mass transfer due to the material consolidation has been experimentally observed. At low evaporating pressure and short cycle time, the mass transfer is the main resistance.

Experimental tests carried out with a chilled ethylene glycol temperature of -7°C with a cycle time of 35 minutes leads to low performances due to a mass transfer resistance, which the COP reaches 0.07 whereas the SCP is 11 W kg^{-1} at 115°C of the heating fluid temperature. Because the effective permeability depends on the evaporating pressure and increase with it (Guilleminot et al., 1998), at this low evaporating temperature, the large mass transfer resistance controls the process during the evaporation step. Besides, the performance parameters are low because there is no heat recovery and mass recovery between the heating and the cooling phases and because the thermal capacity of inert material is not optimized.

Heat and mass transfer both play dominant roles in the performance of the adsorption cooling machine. In a two-bed system, the times of the adsorption and desorption steps (including heating and cooling steps) must be equal. Under these conditions the adsorption phase could become the limiting factor in the design of a new two-bed adsorptive prototype cooling machine.

In conclusion, the adsorbent blocks present good heat transfer properties but the mass transfer resistance is high. Therefore more arteries have to be designed to overcome the mass transfer resistance at low evaporating pressure. Experimental tests performed at low source temperature for ice making show the ability of such an activated carbon—methanol ice-maker driven by waste heat to supply ice with interesting performance. To overcome the problems related to mass transfer resistance, novel highly conductive adsorbent blocks with improved mass transfer properties have been developed. Because the heat recovery operation between two beds can increase the COP by about 25% compared with one adsorber basic cycle system and because the mass recovery may help to obtain a COP increase of more than 10% (Wang, 2000b), a heat and mass recovery cycle has been adopted in the new ice-making prototype. A two-bed adsorptive prototype ice-making machine operating with heat and mass recovery cycle has also been made for onboard adsorption refrigeration in fishing boats. Good performances have been achieved due to improved mass transfer and the average cooling power reached experimentally 3.3 kW, and a mean COP of 0.183 and a mean SCP of 30 W kg^{-1} AC have also been obtained.

Acknowledgments

This work was supported by the State Key Fundamental Research Program under the contract No. G2000026309, National Science Fund for Distinguished Young Scholars of China under the contract No. 50225621, Shanghai Shuguang Training Program for the Talents, the Teaching and Research Award Program for Outstanding Young Teachers in Higher Education Institutions of MOE, P.R.C.

References

Babenko, V.A., L.E. Kanonchik, and L.L. Vasiliev, “Heat and Mass Transfer Intensification in Solid Sorption Systems,” *Journal of Enhanced Heat Transfer*, **5**, 111–125 (1998).

Boubakri, A., M. Pons, F. Meunier, and J.J. Guilleminot, "In Situ, Experiment Study of Three Adsorptive Ice Makers," *Solid Sorption Refrigeration*, pp. 296–301, IIR, Paris, 1992.

Eun, T.H., H.K. Song, J.H. Han, K.H. Lee, and J.N. Kim, "Enhancement of Heat and Mass Transfer in Silica-Expanded Graphite Composite Blocks for Adsorption Heat Pumps: Part I. Characterization of the Composite Blocks," *International Journal of Refrigeration*, **23**, 64–73 (2000).

Fernandez-Seara, J., A. Vales, and M. Vazquez, "Heat Recovery System to Power an onboard NH_3-H_2O Absorption Refrigeration Plant in Trawler Chiller Fishing Vessels," *Applied Thermal Engineering*, **18**, 1189–1205 (1998).

Guilleminot, J.J., A. Choisier, J.B. Chalfen, S. Nicolas, and J.L. Reymoney, "Heat Transfer Intensification in Fixed Bed Adsorbers," *Heat Recovery Systems & CHP*, **13**, 297–300 (1993).

Guilleminot, J.J., F. Poyelle, and F. Meunier, "Experimental Results and Modeling Tests of an Adsorptive Air-Conditioning Unit," *ASHRAE Transactions*, **104**(part 1B), 1543–1551 (1998).

Gurgel, J.M., L.S. Andrade Filho, Ph. Grenier, and F. Meunier, "Thermal Diffusivity and Adsorption Kinetics of Silica- Gel/Water," *Adsorption*, **7**, 211–219 (2001).

Hunan DY Refrigeration Co. Ltd. http://www.dyrefrigeration.com/products/marine/icemaker/index.htm, April 6, 2000.

Liu, Z.Y., G. Cacciola, G. Restuccia, and N. Giordano, "Fast Simple and Accurate Measurement of Zeolite Thermal Conductivity," *Zeolites*, **10**, 565–570 (1990).

Meunier, F., "Solid Sorption Heat Powered Cycles for Cooling and Heat Pumping Applications," *Applied Thermal Engineering*, **18**, 715–729 (1998).

Pons, M. and J.J. Guilleminot, "Design of an Experimental Solar-Powered Solid-Adsorption Ice Maker," *J. Solar Energy Eng.*, **108**, 332–337 (1986).

Poyelle, F., J.J. Guilleminot, and F. Meunier, "Analytical Study of a Gas-Fired Adsorptive Air- Conditioning System," *ASHRAE Transactions*, **102**(part 1), 1128–1138 (1996).

Tamainot-Telto, Z. and R.E. Critoph, "Adsorption Refrigerator Using Monolithic Carbon-Ammonia Pair," *International Journal of Refrigeration*, **20**, 146–155 (1997).

Vasiliev, L.L., N.V. Gulko, and V.M. Khaustov, "Solid Adsorption Refrigerators with Active Carbon-Acetone and Carbon-Ethanol Pairs," *Solid Sorption Refrigeration*, pp. 109–116, IIR, Paris, 1992.

Wang, R.Z., "Adsorption Refrigeration Research in Shanghai Jiao Tong University," *Renewable and Sustainable Energy Reviews*, **5**, 1–37 (2001a).

Wang, R.Z., "Performance of Improvement of Adsorption Cooling by Heat and Mass Recovery Operation," *International Journal of Refrigeration*, **24**, 602–611 (2001b).

Worsoe-Schmidt, P., "Solar Refrigeration for Developing Countries Using a Solid Absorption Cycle," *International Journal of Ambient Energy*, **4**, 115–124 (1983).

Zhu, R.Q., B.Q. Han, M.Z. Lin, and Y.Z. Yu, "Experimental Investigation on an Adsorption System for Producing Chilled Water," *International Journal of Refrigeration*, **15**, 31–34 (1992).