AN ENERGY EFFICIENT SOLAR ICE-MAKER

K.Sumathy
Department of Mechanical Engineering, University of Hong Kong, Hong Kong.
Fax: 852-2858-5415; e-mail: ksumathy@hkucc.hku.hk

Abstract

International environment protection initiatives have led to the intensification of research efforts on development of ozone and global warming safe heat pump technology. Adsorption refrigeration has been intensively investigated in Japan, Europe and USA, because of its promising potential for competing with conventional vapor compression refrigeration. During the last decade, a lot of work has been carried out in this field, with a certain amount of success. To reach a truly practical / applicable and cost effective solar refrigeration technology, some key innovation work must be completed. With the progress in the fields of the adsorbent material production and solar energy collecting technology, there is a real possibility to achieve commercialization of such systems. This paper presents the decription and operation of a solar-powered ice-maker with solid adsorption pair of activated carbon and methanol. A domestic type of charcoal is chosen as the adsorbent , and a simple flat-plate collector with an exposed area of 0.92 m^2 is employed to produce ice of about 4-5 kg/day. Also, it is intended to introduce a hybrid system consisting of solar water heater and ice-maker, which can satisfy the requirements of both the solar ice-making needs as well as good heat collection and heat release in the adsorber. It is expected that by introducing such method using the newly developed ACF, the total efficiency of the system can be increased by about 30 %. This idea is simple and also expected to be effective, since, the hybrid system of solar powered water heater and refrigerator will be able to satisfy both heating and cooling needs, thereby increasing the total efficiency of the system. Although this device is designed just for solar energy utilization, it can be applied to many energy saving fields such as waste heat recovery in industry, and in the exhaust gas-driven air conditioning. Such a novel concept of energy utilization would also contribute to more efficient methods for sustainable development.

1. INTRODUCTION

In recent years, increasing attention is being given to the use of waste heat and solar energy in energising refrigerating systems. Solar powered refrigeration and air conditioning have been very attractive during the last twenty years, since the availability of sunshine and the need for refrigeration both reach maximum levels in the same season. One of the most effective forms of solar refrigeration is in the production of ice, as ice can accumulate much latent heat, thus the size of the ice-maker can be made small.

Solid adsorption refrigeration makes use of the unique features of certain adsorbent-refrigerant pairs to complete refrigeration cycles for cooling or heat pump purposes. Zeolite and activated carbon were used as adsorbents in many systems. In the early 1980's, Tchernev [1] carried out an investigation of adsorption refrigeration with the zeolite+water pair. Also, Pons and Grenier [2] worked on solid adsorption pair of zeolite and water, to produce refrigerating effect achieving a coefficient of performance of only about 0.1. Later, in 1987, they demonstrated that activated carbon and methanol can serve as a suitable pair for a solar powered, solid-adsorption ice-maker. Critoph [3] had studied the performance limitations of adsorption cycles for solar cooling and concluded that, in general, activated carbon-methanol combination was preferable for solar cooling, which giving the best COP achievable in a single-stage cycle. In order to increase the desorption temperature and have a good cooling effect during the adsorption period at night, Headley et al. [4] constructed a charcoal-methanol adsorption refrigerator powered by CPC concentrating collectors, but the solar COP achieved was very low, of about 0.02.

The recent new development of active carbon series - ACF, shows the possibility for applications in adsorption refrigeration. One good example is the development in Byelorussia where a refrigerator prototype using ACF-ethanol and ACF-acetone pairs has been reported [5]. New experiments have been also shown to use a heat pipe for heating/cooling ACF adsorbers for the ACF-NH_3 pair.

In China, work has been carried out on solar powered refrigerators using different adsorption pairs such as calcium chloride+ammonia, Zeolite+water and activated carbon+methanol. In search of new adsorbent materials [6], Wang et al. have reported that, for a specially treated ACF, the measured adsorption capacity of methanol is 2 to 3 times greater than that of normal activated carbon, and the estimated adsorption time is only about 1/5 – 1/10 of that of normal activated carbon. Hence, the recent development of novel adsorbent products and their manufacturing technologies seems to make it possible to achieve new improvements to the performance of solar adsorption units. This paper focus on a solar-powered ice-maker with solid adsorption pair of activated carbon + methanol as well as on the major features of the proposed hybrid system. A simple flat-plate collector having an exposed area of 0.92 m^2 is employed to produce ice of about 4-5 kg/day.

2. TECHNICAL BACKGROUND

Adsorption refrigeration and heat pump cycles rely on the adsorption of a refrigerant gas into an adsorbent at low pressure and subsequent desorption by heating. The adsorbent acts as a 'chemical compressor" driven by heat. Figure 1 shows the schematic of the solar refrigeration system. It consists of a solar collector, a condenser/heat-exchanger and an evaporator that is placed in a refrigerator box. The inside of the collector is lined with an adsorption bed packed with activated carbon absorbed with methanol. The refrigerator box is insulated and stocked with aluminum trays filled with water. The activated carbon can adsorb a large amount of methanol vapor in ambient temperature and desorb it at a higher temperature (around 100 degrees C). During the daytime, the sunshine irradiates the collector, so the collector is heated up and the methanol is desorbed from the activated carbon. In desorption, the liquid methanol adsorbed in the charcoal heats up and vaporizes. The methanol vapor condenses and is stored in the evaporator.

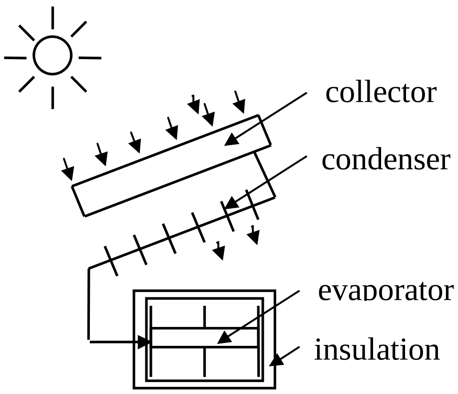

Fig.1 Schematic of a prototype adsorption refrigerator

At night, the collector temperature decreases to the ambient temperature, and the charcoal adsorbs the methanol from the evaporator. The liquid methanol in the evaporator vaporizes and adsorbs the heat from the water contained in the trays. The methanol evaporates at a temperature of about –10 degrees C, so the water temperature can be as low as –5 degrees C and becomes icy. Since adsorption is a process of releasing heat, the collector must be cooled efficiently at night. As mentioned above, the ice maker operates in an intermittent way to produce the refrigerating effect.

The principle of the solid-adsorption ice-maker is explained using a P-T-X diagram as shown in Fig.2. To begin with, the adsorption bed along with the refrigerant gets heated up, and when it reaches the required desorption temperature(T_{d1}), the methanol gets desorbed. In the evening, the flat-plate collector (adsorption bed) looses its heat to the surroundings and hence the temperature of the adsorbent bed is reduced rapidly ($T_{d2} \rightarrow T_{a1}$), and the pressure in the adsorber drops to a value below evaporation pressure (P_e). Evaporation could happen if the connecting valve is open, and ice will be made in the refrigeration box.

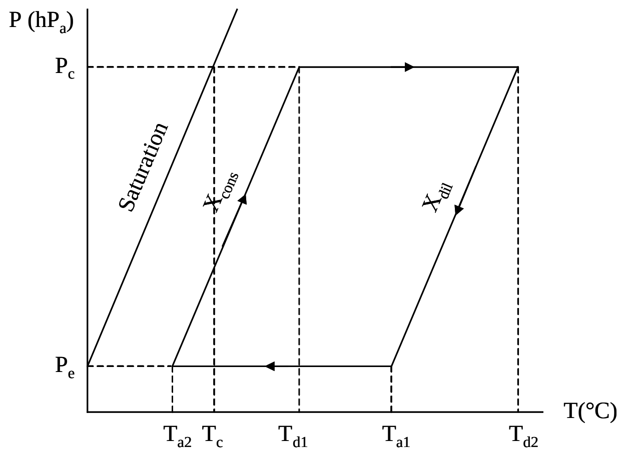

Fig. 2 Thermodynamic cycle for adsorption

As explained above, the system works in an intermittent way. This system can be made to operate continuously to produce ice, by incorporating two absorbers such that while one works in desorption mode, the other would be set in for absorption.

A laboratory prototype system built is capable of producing 4 to 5 kg of ice a day and could achieve a COP of about 0.12. The total size of the ice-maker is about 1 cu m, and weighs about 50 kg. The experimental tests were carried out at various working conditions (-10°C < T_E < -5°C – evaporation; 30°C < T_C < 45°C - condensation; 100° C < T_G < 105°C – generation). The refrigerator performance (Specific cooling power, SCP, and the amount of ice made per day) at the evaporating temperature limits (T_E = -10°C and T_E = 15 °C)are shown in Table 1. The performance is relatively low mainly because of the high cycle time(only one cycle a day).

Table 1. Refrigerator performance at evaporating temperature limits

Evaporation temperature T_E (°C)	Adsorption temperature T_A (°C)	Desorption temperature T_D (°C)	Condensation temperature T_C (°C)	Ice made per day (kg)	Specific cooling power (kg-ice/kg-carbon per day)
- 10	23	100	21	5.1	1.12
-5	31	105	31	4.5	1.01

The full description of the prototype refrigerator built and the analysis of experimental results of the performance of the machine at various working conditions are well documented in yet another paper [7].

3. KEY ISSUES

Several of the disadvantages of adsorption refrigeration have become obstacles for the real mass production of the system. They are (1) long adsorption/desorption time; (2) small refrigeration capacity per unit mass of adsorbant; (3) low COP value. Better design of the adsorber and improvements in the thermal conductivity of the adsorption bed are the main tools to reduce cycle time, while treatment of adsorbent to increase its adsorption capacity on a refrigerant could increase the refrigeration capacity of adsorbent per unit mass and also the COP of the cycle. Recent new developments[1,2] of activated carbon series – activated carbon fibre (ACF) – has called attention to the possibility for application in adsorption refrigeration. For instance, with a specially treated ACF, the measured adsorption capacity on methanol is 2~3 times that of normal activated carbon, and the estimated adsorption time of ACF on methanol is about 1/5~1/10 of that of normal activated carbon [3]. Besides, activated carbon can be made with properties to suit particular applications by varying the activation time and temperature. Hence, with such technologies the specific refrigeration capacity as well as the COP of the adsorption refrigeration cycle can be improved. Studies need to be carried out to validate its potential for possible application in household refrigerators.

Though solar ice making is attractive by an adsorption system, it needs both good heat collecting and heat release characteristics for the adsorber, which seem to be contradictory. It should be noted that, heat release means energy losses. So, in order to make the system more efficient and useful in practice, heat recovery must be considered.

4. PROPOSED TECHNICAL SOLUTION

A hybrid system of solar-powered water heater and ice-maker is one of the alternative to recover heat effectively. This dual purpose system is expected to shorten the cycle time , by shortening the adsorption time, and it is possible for the system to perform more number of cycles a day. The idea is simple but expected to be effective. The adsorber of the ice-maker shall be placed in a water bath which can be powered by a solar collector. Hence, no thermal insulation or enhanced convection are needed for the adsorber, and it can be just immersed in the water bath of the solar powered water heater; which guarantees both good heating or cooling of the adsorber. Therefore, this system would serve as a good combination of solar heating and solar cooling and would improve the overall efficiency (cooling + heating) of the system.

The schematic design of a hybrid solar powered water heater and refrigerator is shown in Fig.3. The system consists of a solar collector, water tank adsorber / generator, condenser, evaporator, receiver, ice-box etc. The working principle is based on the combination of a solar water heater and adsorption refrigeration. In the morning, the solar collector heats the water tank and along with the increase of water temperature, the temperature in the adsorbent bed rises. In an ideal process, the adsorbent temperature could reach a level very close to the water temperature in the tank.

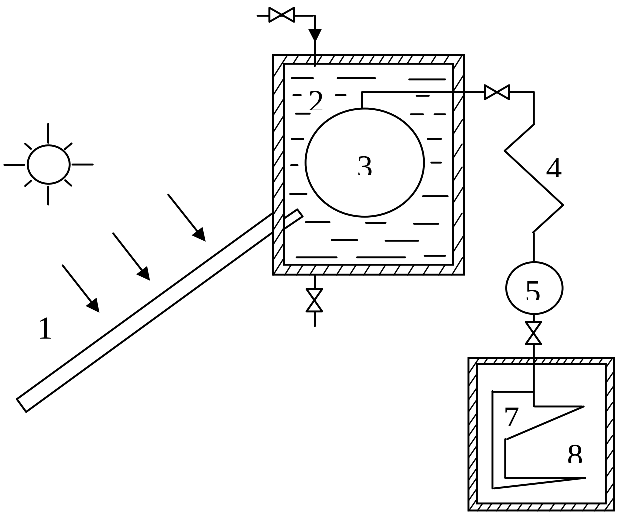

Fig. 3 Proposed improved design

1. Solar collector; 2.water tank; 3. adsorber; 4. condenser; 5. receiver; 7. evaporator; 8. refrigerator

When the temperature in the adsorbent rises up to a temperature which would rise the vapour pressure of the desorbed refrigerant up to the condensing pressure, desorbed vapour would be condensed in the condenser and collected in the receiver. The liquid refrigerant then flows to the evaporator via a flow rate regulating valve. On the other hand the temperature of the water and the adsorbent bed continues to raise to a maximum temperature of about 80-100 °C. The high temperature water is finally drained out into a separate tank, to be used more flexibly for any domestic purposes. With the refilling of the water tank, with cold water, the temperature of the adsorbent bed is reduced rapidly, and the pressure in the adsorber drops to a value below evaporation pressure. Evaporation could happen if the connecting valve is open, and ice will be made in the refrigeration box. The cooling of the adsorber and the rejection of adsorption heat may cause the temperature of cold water in the tank to rise several degrees, however this energy is not being wasted and with refrigeration continuing for the whole night until next morning.

As explained above, the system works in an intermittent way. This system can be made to operate continuously to produce ice, by incorporating two absorbers such that while one works in desorption mode, the other would be set in for absorption.

The features of the proposed hybrid system include: (1) to have a dual-purpose; that is, water heating and refrigeration with one solar collector (which is suitable for household applications); (2) adsorber / generator will be separated from collector, thus a high efficiency can be attained for water heating, along with the heating of the adsorber at the same time. The high efficiency heating does not imply poor cooling of the adsorber through the night, since the hot water from the tank would be drained and will be replaced by cold water; thus the adsorber could be cooled and refrigeration can take place efficiently; (3) energy efficiency will be high for the use of total solar energy collected; (4) there will be no danger of methanol disintegration as the maximum temperature of the adsorption bed cannot exceed 100 °C, due to the water tank. As a first prototype, the unit will be an intermittent one with one working cycle a day.

At the time of writing, preliminary research is underway on the hybrid system and funds are being sought to build a test a complete system.

5. CONCLUSION

Solar-powered refrigeration has a good advantage when compared to other applications. The feasibility of producing ice using solar energy was studied and it was found that it is possible to produce about 4-5 kg of ice per day, with a collector area of 0.92 m^2. It was realised that not only the condensing temperature, but also the adsorption bed temperature has a significant influence on the performance of the system. Also, the maintenance of vacuum in the system can have detrimental effect on the success of experiments. Hence, it is expected that by introducing a hybrid system using the newly developed ACF, the total efficiency of the system can be increased by about 30 %.

6. ACKNOWLEDGEMENT

This work was supported by Committee on Research and Conference Grants (CRCG), the University of Hong Kong, Hong Kong.

7. REFERENCES

1. Tchernev. (1988). Closed cycle zeolite regenerative heat pump. *Heat Transfer Enhancement and Energy Conservatio.* Hemisphere Publ. Co. 747-755.
2. Pons, M. and P.H. Grenier. (1987). Experimental data on a solar-powered ice maker using activated carbon and methanol adsorption pair. *ASME J. Solar Energy Engineering*, 108, 303-310.
3. Pons, M. and J.J.Guilleminot. (1986).Design of a solar powered solid adsorption ice-maker. *ASME J. of Solar Engineering*, 108, 332- 337, 1986.
4. Critoph,R.E. (1988). Limitations of adsorption cycles for solar cooling. *Solar Energy*, 41(1), 23- 31.
5. .Headley,O.S., A.F.Kothdiwala and I.A. Mcdoom. (1994). Charcoal-methanol adsorption refrigerator powered by a compound parabolic concentrating solar collector. *Solar Energy*, 53, 191-197
6. Wang, R.Z., J.P.Jia, Y.H. Zhu, Y.Teng, J.Y. Wu and J. Cheng. (1997). Study on a new solid adsorption refrigeration pair: active carbon fibre-methanol. *ASME J. Solar Energy Engg*, *119*, 214-219.
7. Li Zhongfu and K. Sumathy. (1999). A solar-powered ice-maker with the solid adsorption pair of activated carbon and methanol. *International Journal of Energy Research*, 23, 517-527.