

A SOLAR-POWERED ICE-MAKER WITH THE SOLID ADSORPTION PAIR OF ACTIVATED CARBON AND METHANOL

Z. F. LI AND K. SUMATHY*

Department of Mechanical Engineering, University of Hong Kong, Pokfulam Road, Hong Kong

SUMMARY

This paper presents the description and operation of a solar-powered ice-maker with the solid adsorption pair of activated carbon and methanol. A domestic type of charcoal was chosen as the adsorbent, and a simple flat-plate collector with an exposed area of 0.92 m² was employed to produce ice of about 4–5 kg d⁻¹ at an evaporator temperature of about –6°C. The above system could achieve solar refrigeration COP of about 0.1–0.12. With the description of the idealized refrigerating system, the influences of evaporating temperature, adsorbing temperature and condensing temperature on the COP were also analysed. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: solar energy; solid adsorption; activated carbon and methanol; ice-maker

INTRODUCTION

Solar energy technologies attract world-wide attention owing to their non-polluting nature. Indeed, the technology is matured in some countries and for more than 30 years, exploitation has proceeded. Among various applications, refrigeration is one of the attractive applications of solar energy, because, the amount of sunshine and the need for refrigeration reach maximum levels in the same season. One of the very effective forms of solar refrigeration is the production of ice, because, ice accumulates much latent heat, thus the volume of the ice maker can be small. In 1981, Pons and Grenier (1986, 1987) worked on a solid adsorption pair of zeolite and water, to produce a refrigerating effect and the coefficient of performance was about 0.1. In 1986, they successfully experimented with the adsorption pair of activated carbon and methanol. Similar work was carried out by Exell *et al.* (1987) employing a flat-plate collector which consists of an array of 15 copper tubes. Sakoda and Suzuki (1986), utilizing solar heat, presented the advantages and limitations of the simultaneous transport of heat and adsorbate in a closed-type adsorption cooling system. In order to increase the desorption temperature and have a good cooling effect during the adsorption period at night, Headley *et al.* (1994) constructed a charcoal–methanol adsorption refrigerator powered by CPC concentrating solar collectors, but the solar COP was very low (about 0.02).

In China, Li *et al.* (1980) constructed a solar ice-maker with the absorption pair of ammonia and water. With the exposed collector area of 1.5 m², daily ice production reached 6.8–8 kg, and the solar COP of the system was 0.105, Lin *et al.* (1994) designed a solid absorption ice maker using calcium chloride + ammonia, which could produce ice of about 3.5 kg d⁻¹, with exposed collector area of 1.6 m². Information gathered from the literature reveals that the performance of various solar refrigeration systems varies over a wide range and the reported COP is only about 0.1.

An attempt has been made in the present study to improve the COP of such systems. This paper focuses on a solar-powered ice-maker with solid adsorption pair of activated carbon + methanol. A simple ice-maker

*Correspondence to: K. Sumathy, Department of Mechanical Engineering, University of Hong Kong, Pokfulam Road, Hong Kong.
Email: ksumathy@hkucc.hku.hk

employing a flat-plate collector with an exposed area of 0.92 m^2 was fabricated, which could produce $4\text{--}5 \text{ kg d}^{-1}$ ice.

SYSTEM DESCRIPTION

Figure 1 shows the schematic diagram of a solar-powered adsorption ice-making system. The system consists of a flat-plate collector, a fin-type condenser/heat-exchanger and an evaporator which acts as a refrigerator. The inside of the collector is provided with an adsorption bed which is packed with adsorbent (charcoal), initially being adsorbed with adsorbate (methanol). The evaporator consists of aluminium trays filled with water. During the daytime the adsorbent along with adsorbate gets heated up in the collector, and the adsorbate evaporates from the adsorbent. The vapour is then cooled by the heat exchanger/condenser. The liquid adsorbate is then finally stored in the evaporator to complete the regeneration of the activated carbon.

During the nighttime, the collector cools and hence the temperature of the adsorbent reaches its minimum. In this period of the adsorption process, adsorbate begins to evaporate by adsorbing heat from the liquid (water) and gets adsorbed by the adsorbent in the collector. During this process, the water in the evaporator cools and becomes icy. Since adsorption is a process of releasing heat, the collector must be cooled efficiently at night. As described above, the ice-maker operates in an intermittent way to produce the refrigerating effect.

SELECTION OF THE DOMESTIC ACTIVATED CARBON

There are many adsorption/absorption pairs which could be used for solar ice-making, but the most reasonable pairs are zeolite + water and activated carbon + methanol. For zeolite + water, the adsorbate (water) has a large amount of latent heat (2258 kJ kg^{-1}), which is an advantage for refrigeration. However, water adsorption in zeolite is not so sensitive to variations of temperature, and water ices up easily when the temperature falls below zero, which in turn lowers the system performance. Also, the system COP is less for zeolite + water pair when a simple flat-plate collector is employed. The zeolite + water pair is suitable for refrigeration with higher heat resource temperature (greater than 120°C), and for the purpose of cooling at temperatures above zero. Therefore, when simple flat-plate collectors are used as the heating source, the adsorption pair of activated carbon + methanol is found to be the most suitable pair, to have the optimal refrigerating COP at heating temperatures around 110°C .

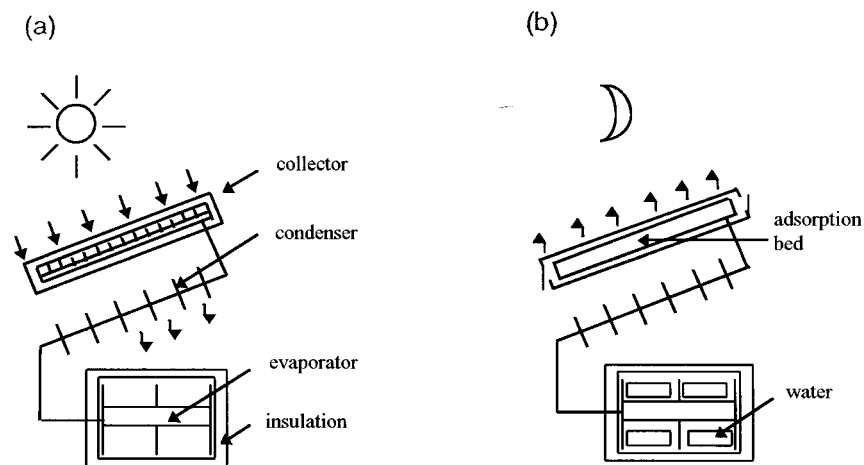
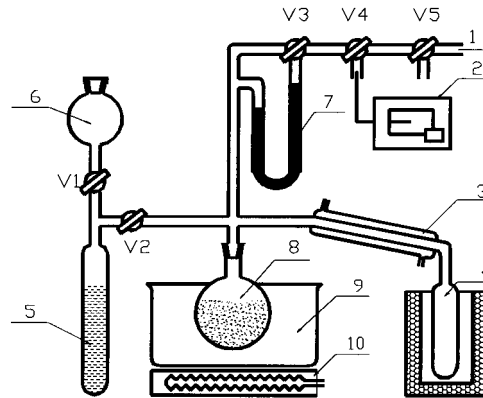


Figure 1. Schematic diagram of the solar-powered solid adsorption ice-maker: (a) daytime (heat/desorption); (b) nighttime (evaporation/adsorption)



1-connect vacuum pump, 2-McLeod-gauge, 3-cooling water (condenser),
4-evaporator, 5-methanol reservoir, 6-methanol inlet bottle,
7-U-gauge(mmHg), 8-activated carbon bottle, 9-oil tank, 10-electric stove

Figure 2. Laboratory glass-tube apparatus for the selection of the activated carbon

Following are some of the other advantages of the solid adsorption pair of activated carbon + methanol for solar ice-making (Pons and Guilleminot, 1986):

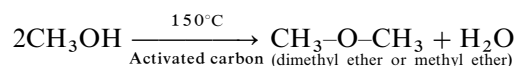
- Methanol can evaporate well below 0°C ; its melting temperature is -93.9°C ; it is easy to produce ice above this temperature.
- Methanol has a small molecular diameter (about 4 \AA), so it can be easily adsorbed in micropores with a diameter less than 20 \AA .
- The boiling point of methanol (65°C at 1 atm pressure) is much higher than room temperature so it needs no leak-proof equipment to evacuate the system at night and to pressurize the system during the daytime. If the boiling point is too low, without the system being evacuated, the liquid would not evaporate easily at night; and without pressurizing to the saturation pressure at room temperature, the vapour could not be liquefied easily.
- The latent heat of evaporation for methanol is significant (about 1100 kJ kg^{-1}), so the cycle COP could reach a higher value.

For the above reasons, this paper focuses on a solar-powered ice-maker with solid adsorption pair of activated carbon + methanol. Activated carbon has a significant volume of micro-pores of convenient size. To choose the best activated carbon for a higher COP, laboratory experiments were conducted for three locally available activated carbons, namely CHK-3, CJK-2, ZX15 (manufactured in China). Figure 2 shows the laboratory glass-tube apparatus for the selection of activated carbon. The activated carbon is placed in a glass jar which is immersed in an oil tank. The oil tank acts as a thermostat and is heated by an electric stove underneath it, and heat is transferred from the oil to the activated carbon to achieve a quasi-uniform temperature. Pressure measurements are made with two manometers of different sensitivities ($0\text{--}0.67 \text{ kPa}$ for McLeod-gauge and $0.13\text{--}26 \text{ kPa}$ for U-gauge). The McLeod gauge is used to measure the system pressure at the beginning of evacuating the system, while the U-gauge measures the pressure of the system during the adsorption/desorption process.

To begin with, the activated carbon kept in the glass jar is heated, in order to evacuate the air occupied inside the micropores of the AC; then, the AC was cooled down and allowed to adsorb methanol. The process of heating and cooling of the AC is carried out 3–4 times in order to completely evacuate the air presented

in the pores of the AC. Later, with the help of a vacuum pump, the system is evacuated to a value of about 10^{-2} mmHg. Then, the activated carbon is allowed to adsorb the methanol from the methanol reservoir by opening valve 2 at room temperature. Once the system reaches the equilibrium temperature, valve 2 is closed and the activated carbon is heated; the methanol gets evaporated and is condensed in the condenser and finally is being collected in the evaporator. The pressure of the system and the actual adsorption quantity of methanol (initial adsorption minus the desorbed quantity which is condensed by cooling water and is being collected in the evaporator) are noted.

Similarly, the same procedure was repeated to evaluate the actual adsorption quantity of methanol by AC, at different temperatures from room temperature to 140°C with a step interval of about 10°C . The above experiment was not conducted beyond 140°C , since above 150°C , the activated carbon undergoes the following reaction with methanol:



To determine the amount of the adsorbate (methanol) being adsorbed by the adsorbent (AC), Dubinin–Radushkevitch equation (Gregg and Sing, 1982) is used:

$$\ln W = \ln W_0 - D [T \times \ln(P/P_0)]^2 \quad (1)$$

where W_0 is the maximum quantity of adsorbate adsorbed by the total volume of the activated carbon micropore system; W is the amount of adsorbate adsorbed by activated carbon to the corresponding adsorbing temperature T and pressure P ; P_0 denotes the saturation pressure of methanol at temperature T ; and D is the structural constant of the adsorbent. According to Gao and Cheng (1984), activated carbon made from coconut presents better adsorption characteristics than that from other materials. Unfortunately, the above-mentioned activated carbon was not available in the local market. Three kinds of domestic activated carbon namely CHK-3, CJK-2 and ZX15 which were available locally were tested and the adsorption data are listed in Table 1. Using this adsorption data, employing Dubinin–Radushkevitch equation and by means of one-dimensional regression, the adsorption parameters of the above three kinds of activated carbon (Table 2) were obtained.

Experiments showed that CHK-3 had better adsorption performance in comparison with the other two AC. Although CJK-2 had nearly the same amount of specific area ($\geq 1100 \text{ m}^2 \text{ g}^{-1}$), its adsorption characteristics were not as good as CHK-3. The large bulk of particles might have resulted in its poor performance. Methanol could not easily enter the inter-micropores of large particles when adsorption takes place and is difficult to evacuate when heated. Also, it was found that for the same amount of adsorption, the time spent on adsorption and desorption for CJK-2 was greater than that for CHK-3. ZX15 cannot be used as the adsorbent because of its small specific area ($\leq 800 \text{ m}^2/\text{g}$) and poor adsorption capacity. Based on the experiments, CHK-3 was chosen as the solid adsorbent for the present study for production of ice.

EXPERIMENTAL WORK

Based on the laboratory experiments, an ice maker with the adsorption pair of activated carbon and methanol was installed, with a flat-plate collector area of 0.92 m^2 (Figure 1). Figure 3 shows the back-view of the solar ice-maker. The collector, aluminium trays to be filled with water in the evaporator, and the condenser are clearly seen in Figure 3. Ventilating windows are provided at the top and bottom of the collector, which would be opened during the adsorption period at night to cause a decrease in adsorption temperature by air convection. Experiments showed that without the windows open, the adsorption temperature of activated carbon could rise to about 5°C above the adsorption temperature, which results in a sharp decrease of COP. 17 kg of activated carbon was loaded inside the collector to form the adsorption

Table 1. Adsorption data for three kinds of domestic activated carbon (charcoal)

| Type | Activated carbon (kg) | Temperature T ($^{\circ}\text{C}$) | Pressure (mmHg) | Adsorption quantity (g kg^{-1}) |
|-------|-----------------------|--|-----------------|--|
| CHK-3 | 0.186 | 80 | 147 | 33.750 |
| | | 90 | 148 | 22.600 |
| | | 100 | 150 | 18.626 |
| | | 105 | 150 | 15.440 |
| | | 115 | 139 | 11.460 |
| | | 122 | 143 | 7.480 |
| | | 125 | 157 | 6.686 |
| | | 130 | 157 | 4.298 |
| CJK-2 | 0.140 | 85 | 145 | 13.532 |
| | | 93 | 144 | 11.940 |
| | | 101 | 144 | 10.348 |
| | | 105 | 144 | 9.552 |
| | | 108 | 144 | 8.756 |
| | | 118 | 155 | 7.960 |
| | | 126 | 163 | 4.776 |
| | | 130 | 187 | 4.378 |
| ZX15 | 0.135 | 74 | 136 | 13.532 |
| | | 82 | 139 | 10.348 |
| | | 90 | 150 | 7.960 |
| | | 100 | 160 | 6.368 |
| | | 110 | 158 | 3.980 |
| | | 115 | 150 | 3.184 |
| | | 125 | 145 | 2.786 |
| | | 135 | 147 | 2.388 |

Table 2. Adsorption parameters for three kinds of domestic activated carbon (charcoal)

| Type | W_0 (g kg^{-1}) | D | R (regression coefficient) |
|-------|------------------------------|------------------------|------------------------------|
| CHK-3 | 0.365 | 1.166×10^{-6} | 0.96 |
| CJK-2 | 0.196 | 8.46×10^{-7} | 0.96 |
| ZX15 | 0.129 | 8.9×10^{-7} | 0.98 |

bed, which is a little less than the specific loading reported by Pons and Guillemot (1986). In order to avoid any deformation of the bed during the operation of the system, several thin aluminium fins of 0.4 mm thick were provided in the bed to add strength to it. The fins also served as a good heat-conducting surface between the collector surface and the adsorption bed of AC. A trough was provided at the bottom of the adsorption bed, to facilitate the collection of methanol being desorbed during desorption process and also to allow uniform distribution of methanol being adsorbed by the activated carbon, during the adsorption process.

Once the adsorption bed was packed inside the collector, the system was evacuated and sealed. The required amount of methanol was injected into the bed, meanwhile, the evaporator was loaded with aluminium trays filled with water. The top and bottom surface of the evaporator were provided with the fins to enhance the heat-transfer. Though it is better to have the evaporator directly immersed in the water tank (for ice production), for efficient results, it is not preferred since, the removal of ice from the tank becomes



Figure 3. Back-view of the solar ice-maker

difficult, and one has to wait until some amount of ice is melted away. Therefore, aluminium trays filled with water were introduced into the evaporator box; though the COP of the system may be a little lower when compared to the direct contact of the evaporator and the water tank.

Unlike in other systems, there is no bypassing tube or valve connecting the collector and the evaporator, directly. Though the adsorption process would be efficient in the earlier case, it is quite inconvenient to operate the valve in the morning and afternoon. Hence, in the present work, the direct contact between the collector and evaporator is avoided, and the methanol vapour is allowed to pass through the U-tube heat-exchanger/condenser, from the evaporator to the collector, during the adsorption process. Since, the time for adsorption is quite long (from 17:00 p.m. to 7:00 a.m. the next morning), the slow adsorption due to the pressure drop could be overcome. Therefore, the present system provides a simple operation of the system and it is proven to be reliable.

The solar operated ice-maker produced ice of about $4\text{--}5\text{ kg d}^{-1}$ when the insolation was about $17\text{--}19\text{ MJ m}^{-2}$. The system COP was around 0.1–0.2. Figure 4 shows the experimental data of the solar ice-maker (for two consecutive days of operation). It can be seen that, good solar insolation was available and the absorber plate could attain a maximum temperature of about $70\text{--}78^\circ\text{C}$. Also, the ambient temperature was low throughout the period of operation, ranging $6\text{--}13^\circ\text{C}$, which enhanced the process of ice-making.

To begin with, the activated carbon gets heated up with the increase in solar radiation, and the desorption process is initiated at around 8:00 in the morning. Later, at the end of the day, as the solar radiation reaches a maximum value, desorption process ceases at around 16:00 p.m. Consequently, the temperature in the evaporator begins to decrease, by the methanol vapour absorbing the heat from the water in the aluminium trays.

The process of adsorption of methanol in the AC is initiated and the process ceases at around 8:00 h in the morning of next day, when solar radiation is available to heat the collector.

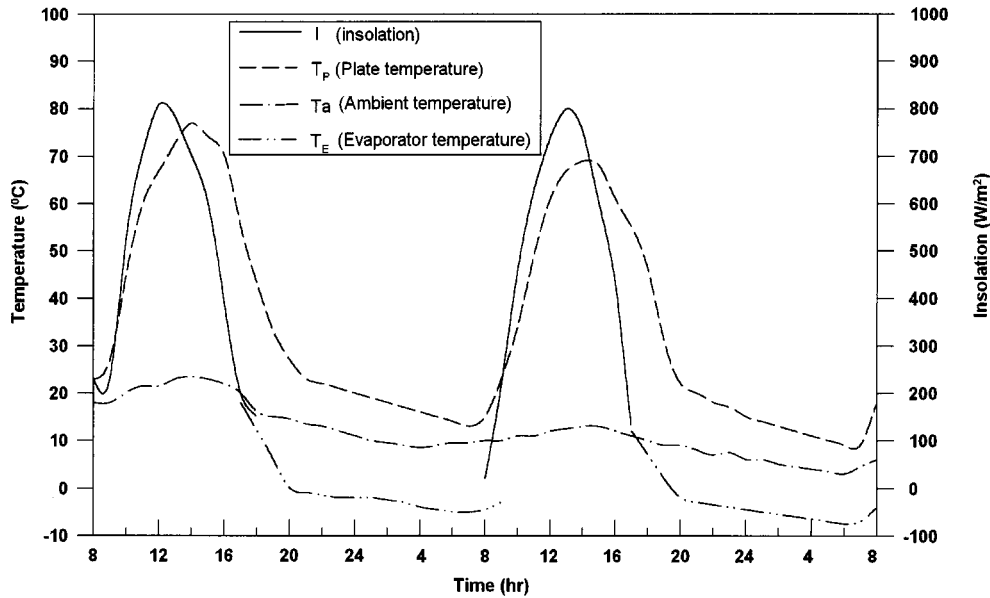


Figure 4. Diagram of operating parameters of the solar-powered ice maker

ANALYSIS OF THE ADSORPTION CYCLE

The principle of the solar-powered solid adsorption ice-maker is explained using Clapeyron diagram ($\ln P$ vs. $-1/T$). Figure 5 shows the idealized process undergone by AC + methanol in achieving the refrigeration effect (producing ice). Let the cycle begin at a point (point A in Figure 5) where the adsorbent is at a low temperature T_A and at low-pressure P_E (evaporating pressure). A–B represents the heating of AC, along with methanol. The collector is connected with the condenser and the progressive heating of the adsorbent from B to D causes some adsorbate to be desorbed and its vapour to be condensed. When the adsorbent reaches its maximum temperature T_D , desorption ceases. Then the liquid methanol is transferred into the evaporator and the collector is closed and cooled. The decrease in temperature D to F induces the decrease in pressure from P_C to P_E . Then the collector is connected to the evaporator and adsorption and evaporation occur while the adsorbent is cooled from F to A. During this cooling period heat is withdrawn both to decrease the temperature of the adsorbent and to withdraw adsorption heat. The total energy input (Q_T) to the system is given by

$$Q_T = Q_{A-B} + Q_{B-D} \tag{2}$$

$$Q_{A-B} = (C_{pa} + C_{pm}W_A)(T_B - T_A) \tag{3}$$

$$Q_{B-D} = \left[C_{pa} + C_{pm} \left(\frac{W_A + W_D}{2} \right) \right] (T_D - T_B) + (W_A - W_D)H_{des} \tag{4}$$

where Q_{A-B} is the heating of the AC + methanol from state point A to state B; Q_{B-D} is the progressive heating of the AC and desorption of the methanol; C_{pa} , C_{pm} are the specific heat of the AC and methanol respectively; W_A and W_D are the initial and the final mass of methanol adsorbed by the AC; H_{des} is the latent heat of desorption.

The cooling effect (for ice production) is given by

$$Q_C = (W_A - W_D) [L - C_{pm}(T_A - T_E)] \tag{5}$$

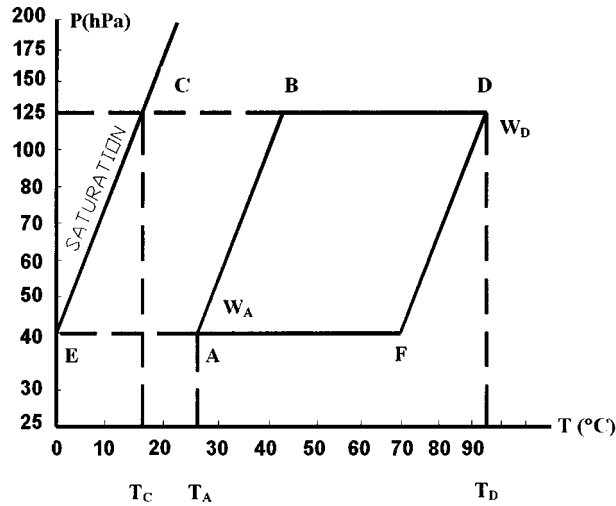


Figure 5. Clapeyron diagram ($\ln P$ vs. $-1/T$) of ideal solid-adsorption cycle

where L is the latent heat of evaporation of the methanol. Therefore, the system efficiency is given by

$$\text{COP}_{\text{TH}} = \frac{Q_{\text{C}}}{Q_{\text{T}}} \quad (6)$$

RESULTS AND DISCUSSION

The correlation of the coefficient of performance, COP_{TH} , with condensing temperature, T_{C} , evaporating temperature, T_{E} , and adsorbing temperature, T_{A} , is obtained for an idealized solar adsorption refrigeration system, neglecting the efficiency of the solar collector. Figure 6 shows the effect of condensing temperature on the COP_{TH} . For a given desorbing temperature, T_{D} , evaporating temperature, T_{E} , and adsorbing temperature, T_{A} , the COP_{TH} decreases with the increase in condensing temperature. This is because, with the increase in condensing temperature, the pressure of the system increases and the amount of methanol desorbed from the activated carbon decreases, which brings down the COP_{TH} of the system. The condensing temperature cannot be too low as it is being restricted by the ambient temperature. Although water cooled condenser may have a good cooling effect, air cooled condensers are widely used in solar ice-making systems. This is because, water-cooled condensers require a water pump to circulate the cooling water or even a cooling tower, this can be applied only for large scale solar refrigeration systems.

A similar effect is observed for the adsorption temperature, T_{A} against COP_{TH} (Figure 7), and as mentioned above, the adsorption temperature is also limited by the ambient temperature. For solar ice-making, the adsorption temperature should be as low as possible during the adsorption period (night-time), and as high as possible during the desorption period (daytime). To attain these two conditions, certain modifications were made to the collector. Windows were provided in the sides of the collector and were kept open in the night to enhance the air circulation and thereby have a good convection effect, bring down the adsorption temperature. Also, flexible insulation was provided at the back of the collector, which was lowered during the adsorption process. For a solar ice-making system, concentrating parabolic/paraboloidal collectors (CPC) are perfected, since these collectors may achieve higher desorption temperature (daytime) and also during the adsorption process, the absorber cools down at a fast rate, thereby bringing down the adsorption temperature.

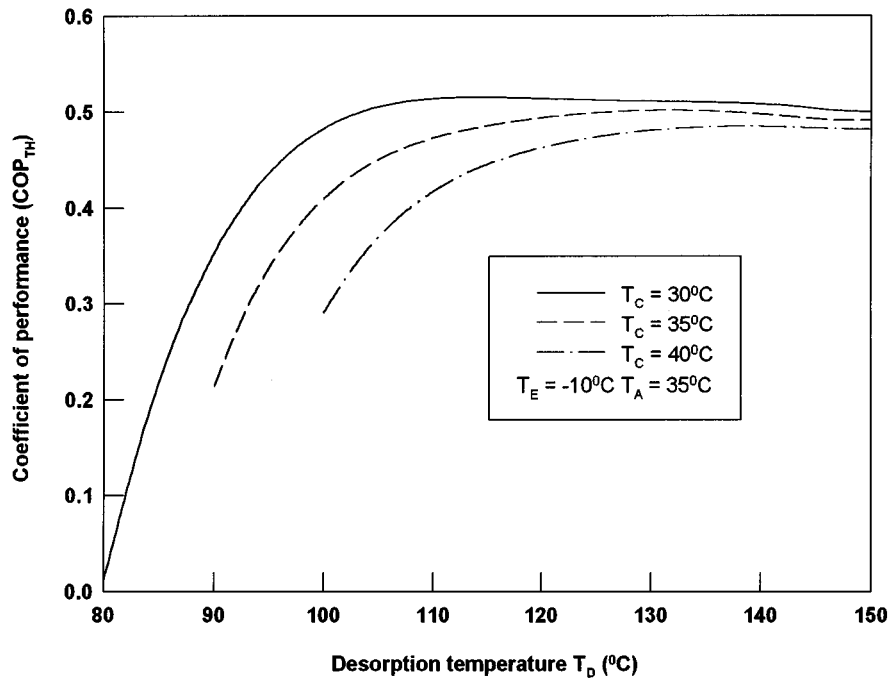


Figure 6. Performance of condensing temperature, T_C

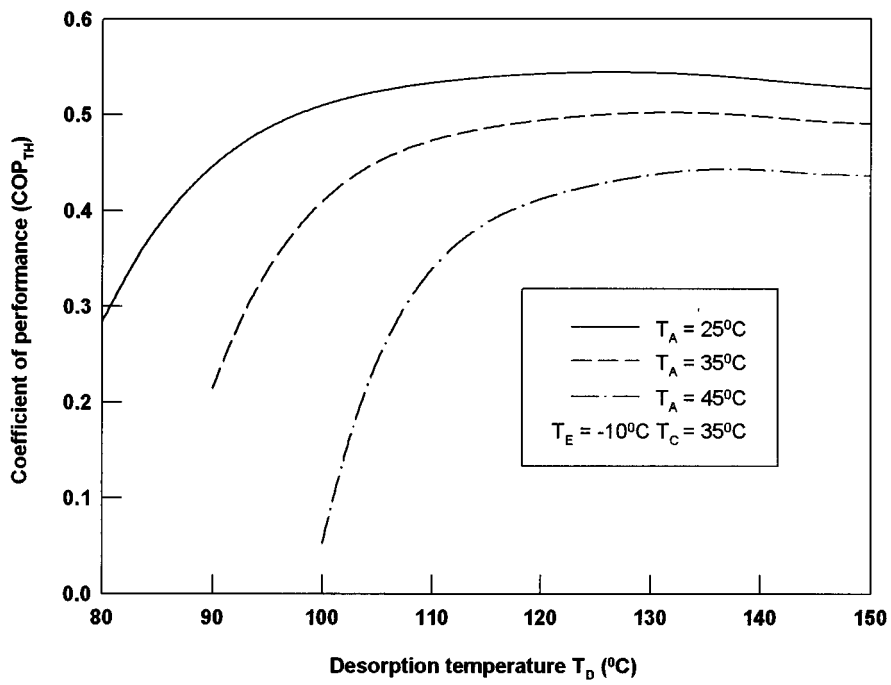


Figure 7. Performance of adsorption temperature, T_A

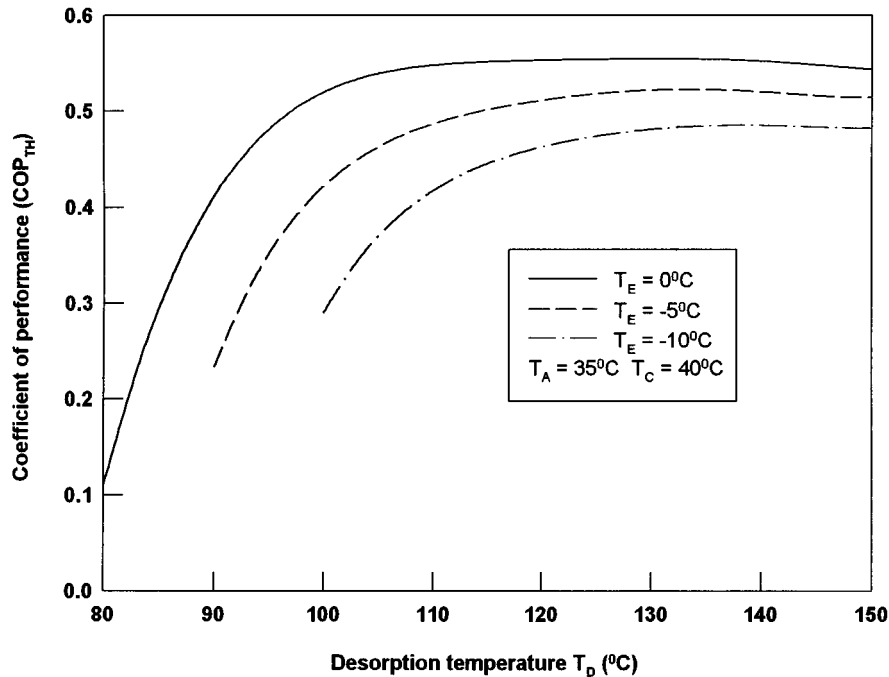


Figure 8. Performance of evaporating temperature, T_E

Figure 8 shows the effect of evaporating temperature on the COP_{TH} . The COP_{TH} decreases with the decrease in evaporating temperature, T_E . For ice making, it is better to control T_E between -5 and $-10^\circ C$, and if for air conditioning, T_E should be around $5^\circ C$. For the solar ice-maker, T_E is determined by the initial adsorbed amount of methanol, W_{in} , and the adsorption temperature. The reasonable way to control the evaporating temperature T_E in the required range, is by controlling the initial adsorbed amount of methanol; because, the adsorption temperature is mostly governed by the surrounding temperature, i.e. the ambient temperature.

From the Figures 6–8, we find that at the desorption temperature of about $110^\circ C$, the system reaches its optimal value of COP_{TH} . This could be achieved by employing simple flat-plate collectors with a selective absorbing-surface. Although a higher desorption temperature can result in a larger amount of cooling, the COP_{TH} of the system may not increase or may even reduce, since the progressive heating causes little desorption of methanol and the extra heat input is mainly utilized in sensible heating of activated carbon and methanol, rather than for desorption. Also, it could be noted that, for a given condensing temperature T_C , adsorbing temperature T_A , and evaporating temperature T_E , the adsorption/desorption cycle require a minimum desorption temperature. For example, in Figure 8, given $T_A \sim 35^\circ C$, $T_C \sim 40^\circ C$ and $T_E \sim 5^\circ C$, if the desorption temperature is below $85^\circ C$, the COP_{TH} would then become negative. This is because, at the temperature below $85^\circ C$, the heat added to the system is only to heat up the activated carbon and methanol and there is no additional energy for the desorption of methanol. At the above said temperature, even if little desorption of methanol is possible, during the adsorption process, the cooling caused by adsorption of methanol is only to cool the methanol in the evaporator to a temperature below zero and there is no extra cooling for ice-making.

CONCLUSION

Solar-powered refrigeration has a good advantage when compared to other applications. The greater the sunshine, the more the ice could be made by the ice-maker, and ice requirement could be large at the same

time. The adsorption pair of activated carbon and methanol is found suitable for solar powered refrigeration as compared with other solid adsorption pairs. The only limitation is, the desorbing temperature of activated carbon cannot exceed 150°C, because the methanol would decompose and the adsorption power of activated carbon decreases sharply at that high temperature. Through the operation of the solar-powered ice-maker, it was found that the initial methanol adsorption quantity, W_{in} , is very important for ice making. Also, the vacuum duration of the system is very important, since a little leak-in of air would decrease the system COP sharply, and sometimes the system would not produce ice at all. The construction of a solar powered adsorption ice-maker is simple and its operation is convenient, since it needs no conventional energy, no rotating parts and no control valve. For a collector area of 0.92 m², it is possible to produce 4–5 kg of ice on a clear sunny day. It is recommended that this kind of solar-powered ice-maker be used for regions where there is abundant of sunshine in the daytime and the environmental temperature is low at nighttime.

REFERENCES

- Critoph, R. E. (1988). 'Performance limitations of adsorption cycles for solar cooling', *Solar Energy*, **41**, 21–31.
- Exell, R. H. B., Bhattacharya, S. C. and Upadhyaya, Y. R. (1987). 'Research and development of solar-powered desiccant refrigeration for cold-storage application', Asian Institute of Technology, Thailand.
- Gregg, S. J. and Sing, K. S. W. (1982). *Adsorption, Surface Area and Porosity*, Academic Press Inc., London.
- Gao, S. Y. and Cheng, W. (1984). *Basis and Application of Activated Carbon*, The Chinese Forestry Publishing House (in Chinese).
- Headley, O. S., Kothdiwala, A. F. and Mcdoom, I. A. (1994). 'Charcoal-methanol adsorption refrigerator powered by a compound parabolic concentrating solar collector', *Solar Energy*, **53**, 191–197.
- Li, S. S., Wang, J. B. and Shen, C. W. (1980). 'An intermittent solar refrigerator with 1.5 m² flat-plate collector', *Acta Energetica Sinica*, **1**, 79–86.
- Lin, G. P., Yuan, X. G. and Mei, Z. G. (1994). 'A new type solar-powered solid-adsorption ice-maker', *Acta Energetica Sinica*, **15**, 297–299.
- Pons, M. and Guilleminot, J. J. (1986). 'Design of an experimental solar-powered solid adsorption ice maker', *J. Solar Energy Engng.*, **108**, 332–337.
- Pons, M. and Grenier, P. (1986). 'A phenomenological adsorption equilibrium law extracted from experimental and theoretical considerations applied to the activated carbon + methanol pair', *Carbon*, **24**, 615–625.
- Pons, M. and Grenier, P. (1987). 'Experimental data on a solar-powered ice-maker using activated carbon and methanol adsorption pair', *J. Solar Energy Engng.*, **109**, 303–310.
- Sakoda, A. and Suzuki, M. (1986). 'Simultaneous transportation of heat and adsorbate in closed type adsorption cooling system utilizing solar heat', *J. Solar Energy Engng.*, **108**, 239–245.