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A novel solar-powered adsorption refrigeration module

N.M. Khattab *

Solar Energy Department, National Research Center, Tahrir street, Cairo, Egypt

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Abstract

This paper presents the description and operation of a simple structure, low cost solar-powered adsorption refrigeration module with the solid adsorption pair of local domestic type charcoal and methanol. The module consists of: a—modified glass tube having a generator (sorption bed) at one end and a combined evaporator and condenser at the other end and, b—simple arrangement of plane reflectors to heat the generator. The testing of the module is mainly focused on the sorption bed, therefore, four types (1–4) of bed techniques and four reflector arrangements (A–D) to heat the sorption bed had been proposed and tested under climatic condition of Cairo (30° latitude). The angles of inclination of the reflectors are varied every month to receive maximum solar energy at noon time. Glass shell is also used to cover the beds in winter.

Test results show that, the module composed of the bed technique Type 4 and reflector's arrangement Type C gives best performance. The time duration during which the bed temperature is above 100 °C was found to be 5 h, with a maximum temperature of 120 °C in winter. In summer, the corresponding values 6 h and 133 °C. During cooling, the minimum bed temperature recorded in either winter or summer time is very close to the ambient temperature due to the absence of bed insulation.

The daily ice production is 6.9 and 9.4 kg/m^2 and net solar COP is 0.136 and 0.159 for cold and hot climate respectively.

Keywords: Charcoal–methanol pair; Glass tube module; Plane reflectors; Solar energy; Solid adsorption refrigeration

* Fax: +20-2-337-09-31.
E-mail address: nag_khb@hotmail.com (N.M. Khattab).

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Nomenclature

Cp	specific heat, kJ/kg K
H	heat of desorption, kJ/kg
L	latent heat of evaporation of the methanol, kJ/kg
m	mass, kg
Q	energy, kJ
T	temperature, °C
Subscripts	
A–D	points on Clapeyron diagram
A.C	activated carbon
c	condenser
e	evaporator
m	methanol
st	steel pieces
T	total

1. Introduction

Solar refrigeration is a useful application of solar energy in areas of the world where there is a demand for cooling high insolation levels, and no firm electricity to supply conventional power systems. One of the very effective forms of solar refrigeration is the production of ice, since ice accumulates much latent heat in it. The most promising application to produce ice by using solar energy is the solid adsorption refrigeration, due to its simple operation and its ability to utilize low grade thermal energy. Although different adsorption pairs had been studied to build adapted solar ice maker, the activated carbon–methanol pair was found the most suitable for solar-powered refrigeration since it could be driven by heat of relatively low, near ambient temperatures. Also it is less expensive than other pairs [1,2]. The adsorption solar refrigerator in its simplest form is a closed system composed of the container of adsorbents and adsorbate (sorption bed), which serves as a solar collector, a condenser and an evaporator. The cycle of this system is divided into two periods: First, the adsorbent is heated by solar energy during the day and the desorbed adsorbate is condensed. Then the adsorbent is cooled after sunset, thereby re-adsorbing the adsorbate, the evaporation of which produces the refrigeration effect. As desorption is highly endothermic, the heat input to the adsorber must be large enough to allow for sufficient refrigerant to be desorped. On the other hand, adsorption is highly exothermal, so, cooling down of the adsorber is also a major concern. Although, the alternation of heating and cooling during the cycle perfectly suits the intermittent nature of solar energy, yet efficient operation of the system requires high rates of heat transfer in and out of the adsorbent. Unfortunately, some problems are encountered which affect rates of heat transfer. First, the heat transfer of adsorbent bed in most current prototype is very poor, due to low convective heat transfer to the adsorber and bad thermal conductivity of the adsorbent. Second, the thermal mass of the container presented an unacceptably high thermal load which affected alternation of heating and cooling. Third, the system suffers from the problem of being tightly sealed against air leakage through the joints and valves which results in degrading the cooling performance. In addition, all solar systems usually suffer from the large variations in ambient conditions between winter and summer, which makes these systems inefficient for part of the year. In solar adsorption systems, while good heating is attained during day time in summer, cooling during night by ambient air will be limited. On the other hand, in winter, the system will attain good cooling during the night, but heating will be insufficient. In the last two decades, different approaches have been developed to improve heat transfer rates and enhance heating and cooling of the adsorbent bed. The use of composite adsorbent blocks [3] and monolithic carbon [4] are useful methods to increase both thermal conductivity and density of the bed. To enhance heating of the beds, flat plate solar collectors with selective surfaces, evacuated tubuler collectors [5], and simple concentration non-tracking collectors as compound parabolic concentrator (cpc) collector [6] have been used. As cooling of the adsorbent is by rejecting heat to the environment, heat loss from the collector to the ambient could be enhanced by means of removable insulation, flaps, or dampers [7]. Some designs combine the collector and finned condenser at one unit since outside fins have been located on the rear surface of the collector [5]. By day the solar collector is a desorber and a condenser. At night, the collector is cooled by the condenser. Recently, simple tubular modules are investigated to be used in the adsorption system in [3,8]. The sorption generator is at one end of the tube and a combined evaporator and condenser are at the other end. In [8], a stainless steel tube with a new monolithic carbon bed was used while in [3], a glass tube with a composite block bed made of silica gel and coated with a thin layer of active carbon was suggested. The works of [3,8], reveal that, using the refrigeration tube is a promising method to overcome some of the problems of the adsorption system.

Therefore, this work presents a novel module composed of a modified glass tube and simple system of plane reflectors. Investigations are focused to improve heat transfer in the adsorbent bed, thereby increasing COP, and to improve external heating and cooling of the bed all year round, thereby realizing good performance of the system for most times of the year.

2. Operation and analysis of the adsorption cycle

The operation principle of the solid adsorption refrigeration system utilizing solar heat is shown in Fig. 1. The system is composed of a container of adsorbents, which serves as a solar collector, a condenser and an evaporator which acts as a refrigerator. A combination of adsorbent and adsorbate is confined in a closed system where no carrier gas exist. The collector is supplied with activated carbon (A.C) which is adsorbed with methanol. During the day-time the activated carbon along with the methanol is heated in the collector. Methanol evaporates from the activated carbon and then is cooled by the condenser and stored in the evaporator. During the night-time, the collector is cooled by ambient air and the temperature of the activated carbon reaches a minimum. In this period, methanol begins to evaporate by absorbing heat from the water to be frozen and is adsorbed by the activated carbon. As the evaporation of the methanol continues, the water temperature decreases until it reaches 0 °C, where ice starts to be formed. The principle of the solid-adsorption ice maker is explained using a Clapeyron diagram ($\ln P$ versus $-1/T$). Fig. 2 shows the idealized process undergone by A.C + methanol in achieving the refrigeration effect

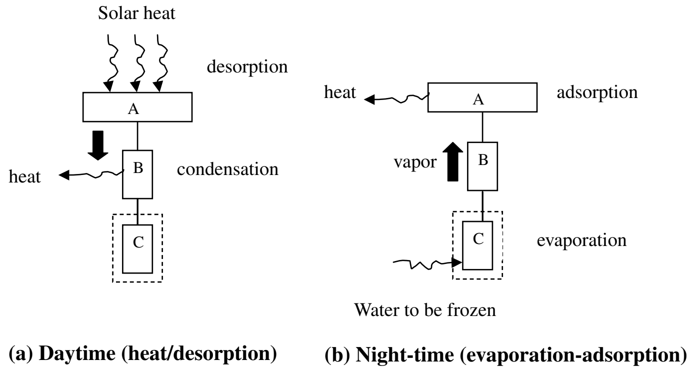

Fig. 1. Operation principle of solid adsorption refrigeration system utilizing solar heat. A: Sorption bed (solar collector); B: condenser; C: evaporator.

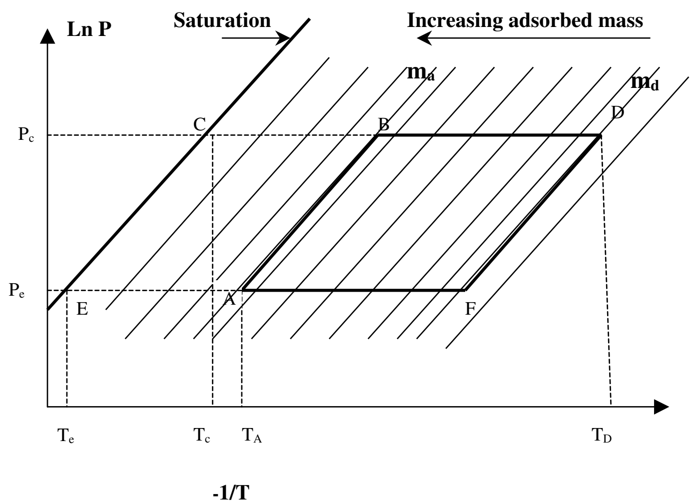

Fig. 2. Clapeyron diagram ($\ln P$ versus $-1/T$) of ideal adsorption cycle.

(producing ice). The cycle begin at a point A where the adsorbent is at a low temperature T_A and at low pressure P_e (evaporator pressure). During the daylight, AB represents the heating of A.C along with methanol. The progressive heating of the adsorbent from B to D causes some adsorbate to be desorbed and its vapor to be condensed at the condenser pressure P_c. When the adsorbent reaches its maximum temperature T_D, desorption ceases. Then the liquid methanol is transferred into the evaporator. During night, the decrease in temperature from D to F induces the decrease in pressure from P_c to P_e. Then the 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.

From the Clapeyron diagram, the total energy gained by the system during the heating period Q_T will be the sum of the energy Q_{AB} used to raise the temperature of the A.C + methanol from point A to B and the energy Q_{BD} used for progressive heating of the A.C to point D and desorption of methanol.

$$Q_T = Q_{AB} + Q_B \tag{1}$$

$$Q_{AB} = (m_{A.C}Cp_{A.C} + Cp_m m_{mA})(T_B - T_A) \tag{2}$$

$$Q_{BD} = [m_{A.C}Cp_{A.C} + Cp_m\{(m_{mA} + m_{mD})/2\}](T_D - T_B) + (m_{mA} - m_{mD})H \tag{3}$$

The gross heat released during the cooling period Q_{e1} will be the energy of vaporization of methanol.

$$Q_{e1} = (m_{mA} - m_{mD})L \tag{4}$$

But the net energy actually used to produce ice Q_e will be

$$Q_e = Q_{e1} - Q_{e2} \tag{5}$$

where Q_{e2} is the energy necessary for cooling the liquid adsorbate from the temperature at which it is condensed to the temperature at which it evaporates.

$$Q_{e2} = (m_{mA} - m_{mD})Cp_m(T_c - T_e) \tag{6}$$

Q_{ice1} is the energy required to cool water from T_A to 0 °C and to produce ice

$$Q_{ice1} = M^*(L^* + Cp_{water}(T_A - 0)) \tag{7}$$

where M^* and L^* are the mass and latent heat of fusion of ice and net cooling produced will be

$$Q_{ice} = M^*L^* \tag{8}$$

3. Performance estimates

The performance estimates of the closed type adsorption refrigeration system could be expressed in terms of

1. The collector efficiency

$$\eta_1 = Q_T/Q_I \tag{9}$$

where Q_I is the total solar energy input to the system during the day.

2. The evaporator efficiency

$$\eta_2 = Q_{ice1}/Q_e \tag{10}$$

3. The cycle

$$\mathrm{COP} = Q_{e1}/Q_T \tag{11}$$

4. The net solar

$$\mathrm{COP} = Q_{ice}/Q_I \tag{12}$$

4. Proposed module

The modified glass tube is shown in Fig. 3a and b. It consists of the sorption bed, the condenser and the evaporator. The sorption bed has been modified from a tube to a circular container with small thickness to increase the exposed area to the sun and insure uniform temperature distribution inside the bed. The sorption bed contains small granules of domestic charcoal (granules diameters are between 5 and 7 mm). The specific surface area of the used charcoal is 55.7 m^2/g and its porosity is 46.45%). To increase bed conductivity, four types of bed techniques are proposed. They are; Type 1, black metallic meshes are placed on both faces of the circular bed, Type 2, black metallic plates are placed on both faces of the bed, Type 3, charcoal grains are mixed with small pieces of blackened steel, and Type 4 charcoal grains are bonded with small pieces of blackened steel. The blackened small pieces are covered with a good metallic binding then mixed with the charcoal and compressed inside the bed. Four types of plane reflector arrangements are used to heat the sorption bed. The details of each type are shown in Fig. 4a–d. The inclination angles of the reflector arrangements A–C are chosen according the analysis made by [9–11], respectively to receive maximum energy input at noon time throughout the year. Table 1 shows the angles of inclination of each type in each month. In the same table, the concentration ratio (the ratio between the solar energy incident on the horizontal due to concentration to that incident without concentration) are also shown. The concentration ratio of reflector Type D is measured experimentally and is found to be 1.75. To reduce losses in cold climate, a glass shell shown in Fig. 4e will be used to cover the sorption bed.

4.1. Advantages of the proposed module

1. Each module can represent a refrigeration unit. A refrigeration system consisting of many such modules has the advantages of simple structure and low cost.

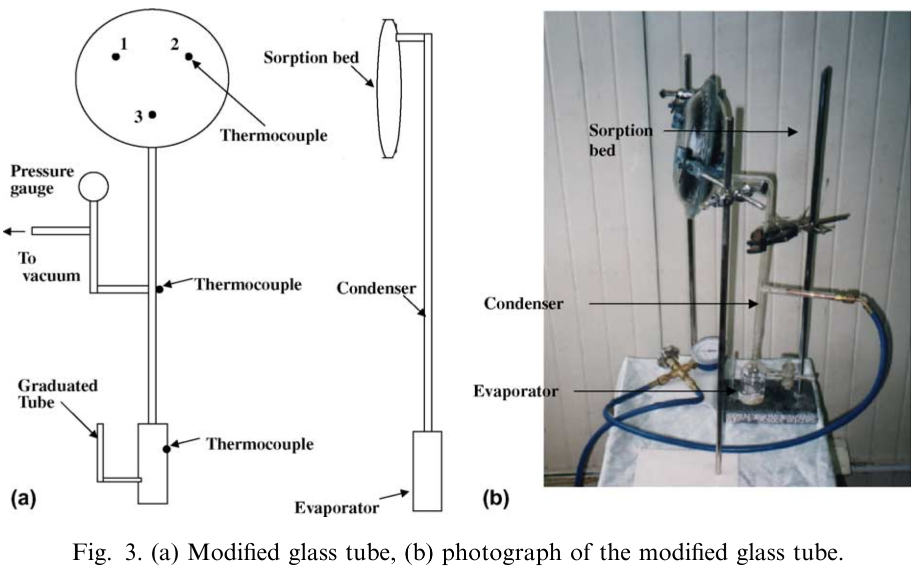

Fig. 3. (a) Modified glass tube, (b) photograph of the modified glass tube.

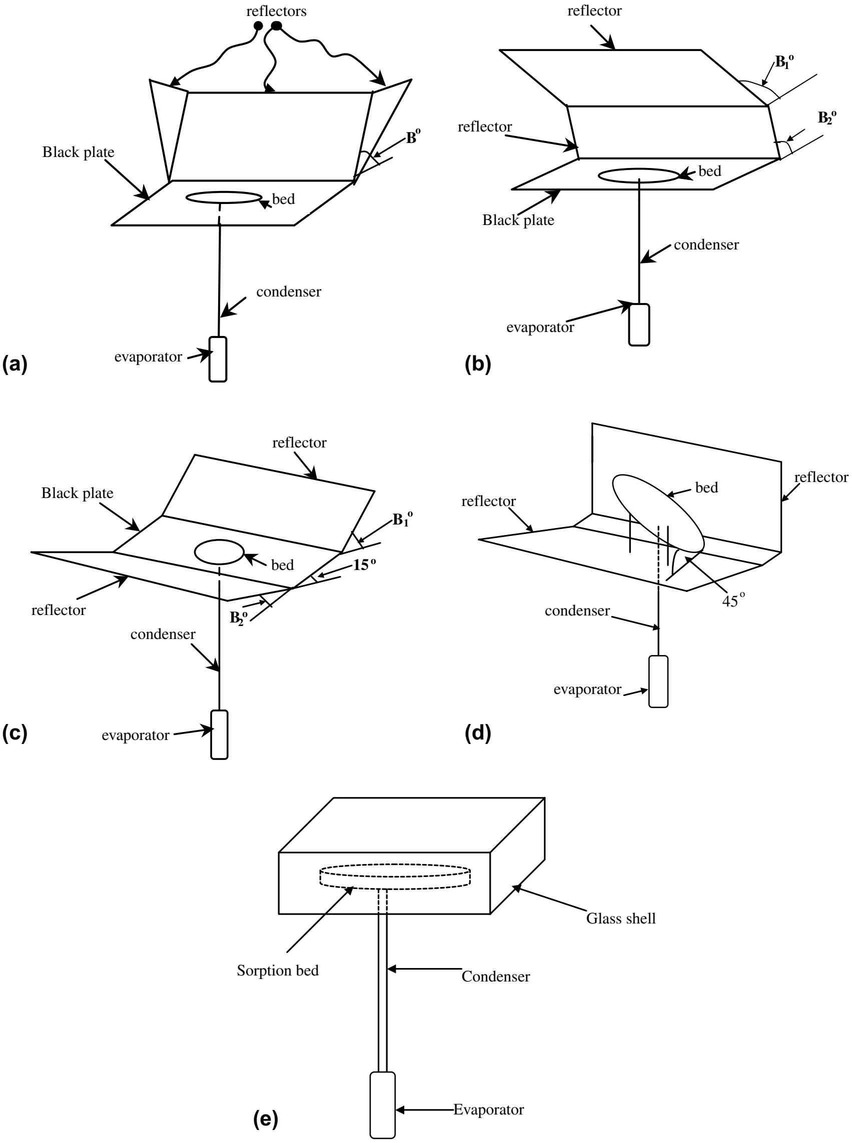

Fig. 4. Reflector arrangements: (a) Type A, (b) Type B, (c) Type C, (d) Type D, (e) glass shell.

2. As metal bed is avoided, glass adsorbent bed enables solar energy to be absorbed directly through the glass. So, the effectiveness of solar energy is enhanced.
3. The circular container increases the absorbing surface area and its small thickness insure uniform temperature distribution inside the bed.
4. Having the sorption bed, the condenser and the evaporator all in one part, air leakage is zero.
5. Using materials having high thermal conductivity inside the adsorber not only increases thermal conductivity inside the bed, but also increases bed temperature, due to its high absorptivity of solar energy.

Table 1
Inclination angles and concentration ratio CR for different reflectors arrangements

	Type A		Type B			Type C		
Months	B°	CR	B_1°	B_2°	CR	B_1°	B_2°	CR
January	94	1.9	110	94	1.9	100	23	2.02
February	89	1.87	107	90	1.85	94	28	1.96
March	80	1.63	100	83	1.8	87	34	1.9
April	73	1.45	90	72	1.77	78	42	1.87
May	68	1.35	83	70	1.66	71	50	1.85
June	66	1.25	80	65	1.6	69	52	1.85
July	68	1.3	82	67	1.65	69	50	1.78
August	74	1.4	95	72	1.78	75	43	1.88
September	80	1.5	97	82	1.8	85	36	1.9
October	92	1.75	104	90	1.9	92	28	1.95
November	89	2.0	110	93	1.92	97	22	2.05
December	96	1.91	112	97	1.95	101	20	2.1

6. Plane reflectors can provide high-performance, low cost configurations for solar energy concentration.
7. The heating arrangements heat both faces of the sorption bed and thus, ensure sufficient and uniform heating during the day. In this way, there will be no need to use insulation which prevents effective cooling of the bed during the night.

5. Experiments

The proposed module shown in Fig. 3 has the following dimensions; circular bed of 0.2 m diameter and 0.05 m thickness. The bed contains 0.6 kg of charcoal grains and 0.2 kg of small pieces of steel. The glass bed thickness is 0.003 m. The condenser is a glass tube of 0.5 m long and 0.015 m diameter. The evaporator is a cylindrical glass with 0.05 m diameter and contains 0.2 kg of methanol. It is wrapped with foamed polystrol resin of 100 mm thickness. A graduated glass tube is connected to the evaporator to show the methanol level in the evaporator. Each plane reflector is of 0.2×0.2 m wood plate covered with aluminum foil sticker.

Five thermocouples K-Type are used to measure temperatures with uncertainty equal 0.5 K, (three for the bed, one for the condenser and one for the evaporator). Their locations are shown in Fig. 3. Multichannel Recorder Model AH520-ONN-NO. AH95A001 is used to record the temperatures. Data Logger weather station type (Delta-T Logger DL 2e) is used to record ambient conditions and incident solar radiation on horizontal surface with uncertainty equal 1.7. Pressure gauge is used to measure the pressure inside the module. The accuracy of the daily ice production is about 4%.

The experimental work included two parts:

(1) Heating and cooling the adsorbent bed without mass transfer under three conditions:
   1. different bed techniques,

2. different reflector arrangements,
3. using glass shell over the bed.

(2) The performance of the module as a refrigerator (heat and mass transfer).

6. Results and discussion

6.1. Results of the first part

Figs. 5–8, show the effect of different bed techniques, reflector arrangements and using glass shell on the bed temperatures during heating and cooling over 24 h. The measured average temperatures of the four types of beds when heated by the reflector Type D at the end of February are shown in Fig. 5. In the same figure, measured ambient temperature and solar intensity incident on horizontal plane are also drawn. For comparison, measured temperatures of a plain bed contains charcoal only and heated by direct solar energy are also drawn. It is clear that improvements in the temperatures of the different beds are achieved as a result of using different bed techniques. It is also clear from this figure that, by virtue of mixing charcoal with metallic

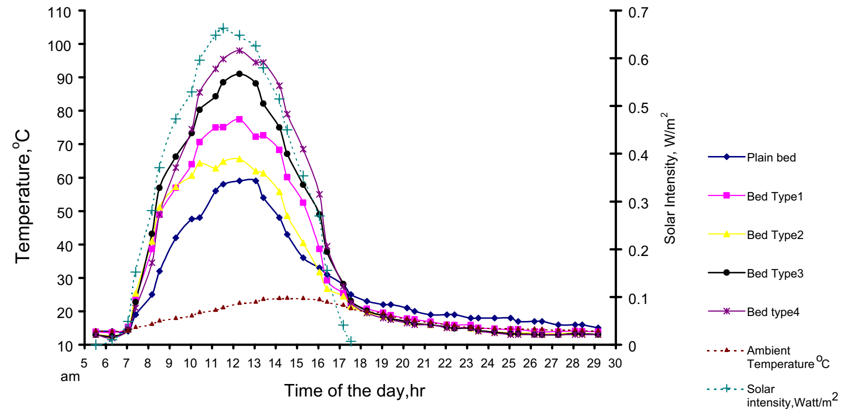

Fig. 5. Measured average temperature of the four types of bed techniques (February).

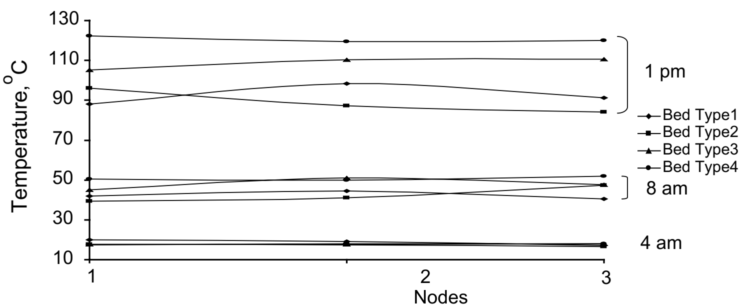

Fig. 6. Temperature distribution inside the four types of bed techniques at different times of heating (February).

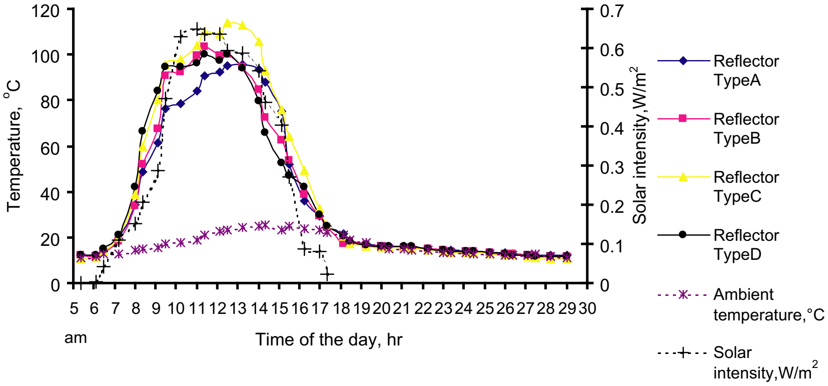

Fig. 7. Effect of reflector arrangements on the temperature of bed Type 4 (February).

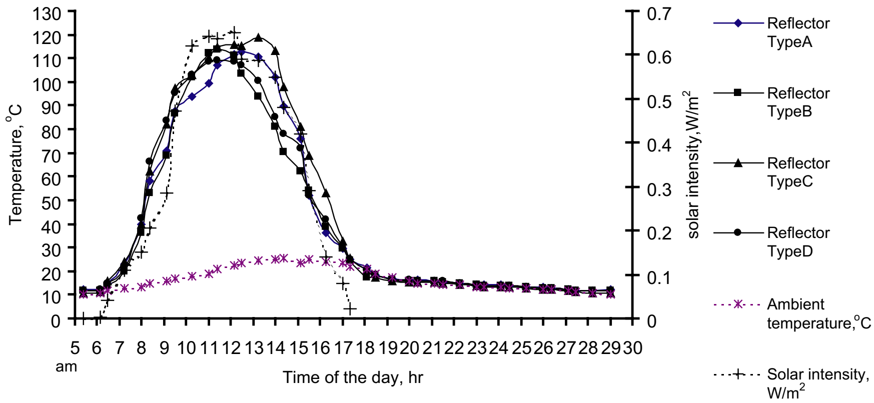

Fig. 8. Effect of using glass shell on bed temperatures Type 4 for different of reflector arrangements (February).

pieces, bed techniques Types 3 & 4 attained higher temperatures than Types 1 & 2. Maximum temperature recorded is for the bed Type 4, it reaches 95 °C for about 2 h. This temperature is higher by 60% than the temperature of the plain bed heated directly by solar energy. This figure also shows that the temperatures of all beds during cooling at night are very close to the ambient temperature. Fig. 6 shows the temperature distribution inside the four beds at different times of heating. Good temperature distribution inside the beds Types 3 & 4 are observed specially at high temperatures as a result of mixing metallic pieces with charcoal.

The effect of different reflector arrangements on the temperature of the bed Type 4 is shown in Fig. 7. It is observed from this figure that, bed temperatures for all reflector arrangements exceeds 90 °C. The bed temperatures heated by reflector Type C stay 100 °C for time duration 4 h and the maximum temperature recorded is 115 °C. This temperature is higher by about 13.5% than the maximum temperature recorded when this bed is heated by reflector arrangement Type D.

Although reflector Type D does not realize the maximum bed temperature during heating, it has the advantage of fixed orientation over the whole year (the orientation of Types A–C must be changed monthly to attain maximum energy input at noon).

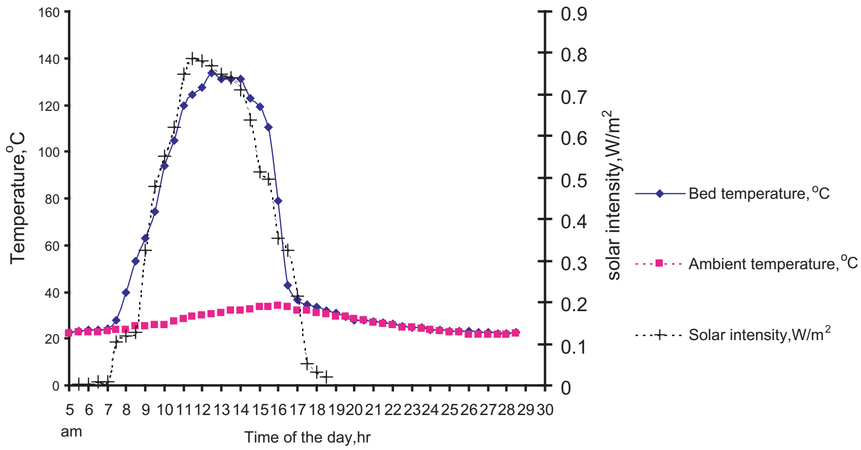

Fig. 9. Temperature of bed Type 4 when heated by reflector Type C (June).

The effect of using a glass shell on the bed temperatures in cold weather is shown in Fig. 8. As expected, an increase in bed temperatures for all types of reflectors are recorded. The time duration at which the bed temperature stay 100 °C was found to be 5 h for the bed heated by reflector arrangement Type C and maximum temperature recorded is 120 °C. An increase of about 9% is achieved in bed temperature as a result of using glass shell.

It is quite evident that the module composed of the bed technique Type 4 and reflector Type C realize the best performance when tested in cold climate. This module is tested in June (summer season) without using the glass shell. Fig. 9 shows measured average bed temperature, ambient temperature and solar intensity over 24 h. From this figure, bed temperature was found to be 100 °C for about 6 h and maximum bed temperature was about 133 °C. The bed temperatures at night are observed to be the same as ambient temperature.

6.2. Results of the second part

6.2.1. Module preparation

Prior to experiments, module preparations are carried out. In order to purge water vapor and other gases adsorbed on charcoal particles packed in the bed, it was evacuated for about 15 min while its temperature is kept at 100 °C. Then the evaporator is filled with the methanol and evacuation was continue for over 10 min until methanol boiling is observed. Desorbed mass is measured at the beginning and the end of the heating period, then the water container is set outside the evaporator and well insulated. In early morning on the second day the ice formed around the evaporator is carefully released.

The performance of the module composed of the bed Type 4 and reflector Type C, is studied as a refrigerator in hot and cold climate (June and November). Table 2 shows the experimental results of the proposed module. Temperatures and pressures defined in Clapeyron diagram as well as the module performance are illustrated in this table.

Table 2
Experimental results of the proposed module

Results	June	November
The initial or lower generator temperature T_A, °C	23.5	14
The bed temperature denoting the start of adsorbate condensation T_B, °C	39.2	28.1
The maximum generating temperature T_D, °C	130	114
The average condenser temperature and pressure (T_c, °C & P_c, kPa)	33, 22	24, 12.5
The minimum evaporator temperature and pressure (T_e, °C & P_e, kPa)	−1.0, 4	−1, 0.4
Maximum and minimum ambient temperatures, °C	35.1/23	25.87/14
The desorbed mass of the methanol, kg	0.162	0.12
The produced mass of ice, kg	0.28	0.206
Q_I, MJ/m^2/day	20.063	17.197
Q_T, kJ	352.2	284
Q_{e1}, kJ	178.2	132.2
Q_e, kJ	170.9	128
Q_{ice1}, kJ	116.5	92.2
Q_{ice}, kJ	90.9	80
η_1	0.559	0.526
η_2	0.66	0.72
Cycle COP	0.505	0.464
Net solar COP	0.159	0.136

It is to be noticed:

1. The physical properties used to calculate different quantities in Table 2 are as follows:
   - Methanol [1]: $H = 1400$ kJ/kg, $L = 1100$ kJ/kg and $Cp_m = 1.34$ kJ/kg K.
   - Charcoal [4]: $Cp_{A.C} = 802.51 + 2.811T$ J/kg K, where T is in K.
2. The thermal inertia of the steel pieces in the bed is taken into consideration when calculating Q_T. Thus Eq. (1) becomes;

   $$Q_T = Q_{AB} + Q_{BD} + Q_{st}$$

   where $Q_{st} = m_{st}Cp_{st}(T_D - T_A)$.

Table 2 reveals some important results that affect the module performance

1. Input solar energy Q_I in cold climate becomes comparable with that of hot climate since concentration ratio in cold climate increases by about 10% than in hot climate (as is clear from Table 1).
2. The bed temperature and total energy gained in cold climate become comparable with those of hot climate as a result of using glass shell. So, the collector efficiency in winter was found to be about 94% of that in summer.
3. The effect of the minimum temperature of the ambient air T_A on the module performance appears as a lost of the part of the cooling energy transferred from the evaporator Q_{ice1}. This lost energy is used to reduce water temperature from T_A to the evaporator temperature (0 °C). As T_A increases in hot climate, this lost energy also increases. It was found to be 12% and 22.6% of the cooling energy for cold and hot climate respectively.

Table 3
Comparison between COP of the present work and other works

	Pair	Cycle COP	Net solar COP	Q_I, MJ/m^2/day
[1]	Activated carbon and methanol	0.43	0.12	20
[12]	Activated carbon and methanol		0.1	19
			0.12	22
[13]	Activated carbon and methanol AS-Ac-35		0.156	
			0.13	
[14]	Activated carbon and methanol		0.12	
[15]	Activated carbon and methanol		0.1	17
			0.12	19
Present work	Domestic charcoal and methanol		0.136	18
			0.159	20

Table 3 shows the COP of the present module and other adsorption systems working under nearly the same solar energy collected per day. From the figures listed in this table, it is evident that the present module realizes the same or better performance rather than the works of the others.

7. Conclusions

Simple structure, low cost, solar-powered adsorption refrigeration module had been designed and tested. The module composed of a modified glass tube and simple system of plane reflectors. The modified glass tube includes the sorption bed, the condenser and the evaporator as a one part. Investigations are focused to improve heat transfer in the adsorbent bed and to improve external heating and cooling of the bed all year round. Four types (1–4) of simple bed technique are proposed to increase bed temperature during heating. Four types (A–D) of plane reflector arrangements are proposed to heat the sorption bed. These arrangements can provide high-performance, low cost configurations for solar energy concentration and are ideally suited to heating in winter. The concentration ratio of these reflectors are from 1.7 to 1.8 in summer and from 1.9 to 2.1 in winter respectively. Glass shell is used in cold climate to reduce top losses from the bed. Bed insulation is eliminated to help good cooling during night. Cheap kind of charcoal was used as adsorbent.

It is found that using the four types of bed techniques heated by reflector Type D in cold climate can increase maximum bed temperature by a ratio between 13% and 60% than the plain bed temperature heated directly by solar energy. The bed Type 4 heated by reflector arrangement Type D achieve the maximum increase. This bed achieved an increase of 13.5% when heated by reflector arrangement Type C. The temperature of the same bed increased by about 9% when glass shell was used. The maximum bed temperature of the module composed of bed Type 4 and reflector arrangement Type C was found to be 120 and 133 °C in cold and hot climate respectively. The minimum bed temperature at night was found to be is very close to ambient temperature in both winter and summer. Testing module as a refrigerator realize daily ice production of 6.9 and 9.4 kg/m^2 and net solar COP of 0.136 and 0.159 in cold and hot climate respectively.

8. Future work

Domestic charcoal, with its low price, when used as adsorbent realize good performance as compared with another types of activated carbon. However, using activated carbon must be studied from the economical point of view. Further study for the determination of the optimum percentage of the steel pieces mixed with the charcoal in the bed is also needed.

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