

Experimental Study of Absorptive Solar Powered Refrigerator in IBADAN (Nigeria) - 1: Performance in Actual Site

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ABSTRACT

Industrial refrigeration is one of the most energy consuming sector in the world today. In a world where electrical energy cost is increasing exponentially, the need for a refrigeration system that utilises minimal amount of energy becomes paramount. The solution lies in adsorption refrigeration system which is powered by heat energy from the sun. It is in this light, that a model to carry out the analysis of Activated carbon/Methanol pair for an adsorption ice-maker has been developed. Which will also help to determine the efficiency of the system using this same pair.

The design calculations were carried out using mathematical analysis which was obtained by means of weight and energy balance in addition to the relations between temperature, pressure, concentration and enthalpy of the working fluids (refrigerant and the adsorbent) and the energy source (Solar energy). For the fabrication of the system, quality seamless copper tubing (of BS EN 1057) was used for the pipe network. For this pipe network, series of 40mm and 30mm pipes were placed concentrically while their ends were welded together to form the reactor section and 25.4mm tubes were considered for the condenser and evaporator section. Perplex sheet and fibre glass were used for the evaporator compartment, flat plate solar collector for collection of the required heat energy, while the condenser tube was designed to be water-cooled in a concrete compartment.

During operation of this prototype, the solar insolation rose steadily from 80W/m² at 8:00a.m to 926W/m² at about 2:00p.m. During this period, the temperature of the adsorber bed also rose to a peak value of 98°C, which was one of the highest recorded. With this level of insolation, the adsorbent desorbed effectively while the temperature of the cooling water rose by 5°C. The evaporator pipes' temperature decreased gradually from about 35°C at 7:00pm until it reached a minimum value of 15°C at 2:00am. With this result, a C.O.P of 0.025 was recorded.

Keywords: refrigeration, Energy, Adsorption, Solar

1. INTRODUCTION

The interest in solar powered adsorption systems started to attract worldwide attention owing to their non-polluting nature, also due to the oil crisis in the 1970s that lead to a concern about the energy shortage, and then later, in the 1990s, because of ecological problems related to the use of CFCs and HCFCs as refrigerants. Such refrigerants do not tend to be more expensive but also, when released into the atmosphere, depletes the ozone layer and contribute to the greenhouse effect. Furthermore, due to increase in energy consumption worldwide, it is becoming even more urgent to find ways of using the energy resources as efficiently as possible. Thus machines that can recover waste heat at low temperature levels, such as adsorption machines have proven to be an interesting alternative for wiser energy management owing to achievements attained by different experimental work that have been carried out in various part of the world.

The conventional adsorption cycle mainly includes two phases:

- 1) Adsorbent heating with desorption process, also called generation, which results in the refrigerant condensation at the condenser and heat release into the environment. The heat necessary for the generation process are usually supplied by low-grade heat source, such as solar energy, waste heat, etc.
- 2) Adsorbent cooling with adsorption process, which results in refrigerant evaporation inside the evaporator and thus, the desired refrigerated effect. At this phase the sensible heat and adsorption heat are consumed by the cooling medium, which is usually water or air.

This adsorption cycle were presented extensively in literature ^[1-3].

Adsorption solar cooling units have been widely studied in late 70s and gave rise to prototypes using the performance of mainly four pairs:

- Activated carbon (AC) – methanol [1];
- Silica gel – water [2,3];
- Zeolite – water [4,5];
- Activated carbon–ammonia [6, 7].

Activated carbon obtained from olive stones and almond shells has high metal ions adsorption capacities [8]. Plum and peach stones have also been used for preparation of activated carbon [9]. The carbons from peach stones have also shown narrow pore size distribution and good properties as molecular sieves. The adsorbents prepared from plum stones had a better porosity compared to those prepared from peach stones.

The preparation of these activated carbons is economical and they have, besides some special properties, good adsorptive properties and hardness, which could be of interest in future environmental protection programs. Nearly all-inexpensive carbonaceous materials can be considered as starting materials for the production of activated carbon [10]. The starting material and the method of preparation influence the quality of the resulting activated carbon [11]. This present work utilises carbon adsorbents prepared from olive stones (OS), which are waste by-product with significant amounts in the oil industry.

The basic operations of an adsorption refrigeration unit involve freeing the refrigerant from its bonds with the adsorbent material and then condensing it under pressure. Figure 1 show this cycle in its simplest form. It consists of two linked vessels, one of which contains adsorbent and both of which contain refrigerant. Our preferred adsorbent and refrigerant are activated charcoal and methanol.

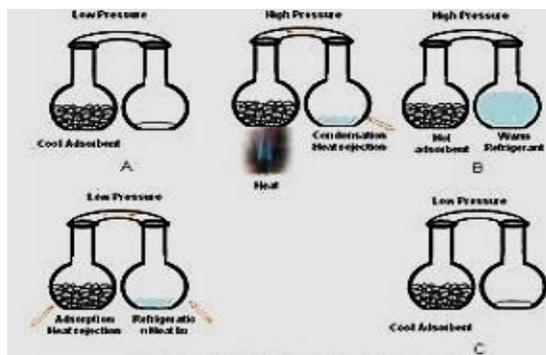


Figure 1 A simplified Adsorption cycle Schematic

Initially the whole assembly is at low pressure and temperature, the adsorbent contains a large concentration of refrigerant within it and the other vessel contains refrigerant gas.

The adsorbent vessel (generator) is then heated, driving out the refrigerant and raising the system pressure. The desorbed refrigerant condenses as a liquid in the second

vessel, rejecting heat; this is part of the useful heat output of a heat pump. Finally the generator is cooled back to ambient temperature, re-adsorbing the refrigerant and reducing the pressure. The reduced pressure above the liquid in the second vessel causes it to boil, absorbing heat and producing the refrigeration effect. The heat rejected by the generator forms the other part of the useful heat output of the heat pump. The cycle is discontinuous since useful cooling only occurs for one half of the cycle. Two such systems can be operated out of phase to provide continuous cooling [12]. Such an arrangement has a comparatively low Coefficient of Performance (Refrigeration COP = Cooling / Heat Input and Heat pump COP = Heat Output / Heat Input). Also, since the thermal conductivity of the bed is generally poor, the time taken for a cycle could be an hour or more and the cooling power per mass of adsorbent could be less than 100 W/kg.

2. THERMODYNAMIC ANALYSIS OF THE CYCLE

A brief static thermodynamic analysis of a typical ideal adsorption refrigeration cycle is presented. With the adsorptive property of the working pair determined using the $P - T - X$ relationship-based adsorption equation (D-A equation), static thermodynamic analysis can be conducted as follows. Figure 2 illustrates an ideal adsorption refrigeration cycle presented in a P-T-X diagram. For a given working condition, the ideal cycle in a P-T-X diagram has a fixed shape[13]. Position of point 1 is determined by the evaporating pressure and cooling source temperature (T_1 is the minimum temperature of the generator, i.e. carbon). Point 2 depends on the condensing pressure or temperature while point 3 is determined by the highest temperature of the heat source. Finally the position 4 depends on the evaporation pressure.

The calculation of two significant evaluation criteria of an adsorption refrigeration system, i.e. refrigeration output Q_r and refrigeration COP, can be achieved with the following static analysis.

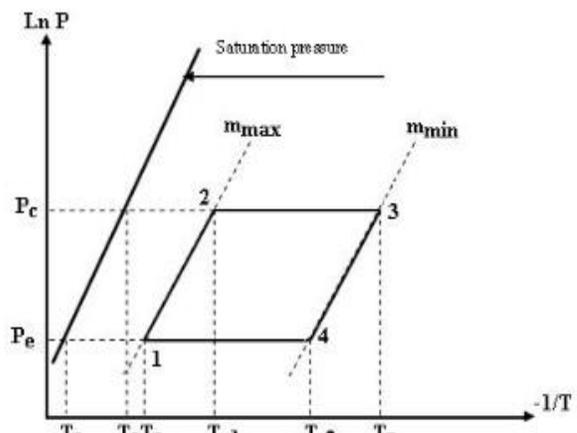


Figure 2 P-T-X diagram of an ideal basic adsorption refrigeration cycle

Process 1: Isosteric Heating (1 – 2)

Within this process, heat is supplied to heat up adsorbent (activated carbon) together with adsorbate that was trapped in the micropores of activated carbon particles. Concentration of methanol in the carbon in this process remains unchanged. When energy losses in the heat transfer and heat supplied to the metal tube are not taken into account, energy input in this process can be calculated by Eq. 3.3.

$$Q_{1-2} = (C_{ac}M_{ac} + C_rM_{r1})(T_{c1} - T_a) \quad (1)$$

Where: Q_{1-2} is heat supplied to heat up activated carbon and methanol from point 1 to point 2; c_{ac} and c_r represent heat capacities of activated carbon and refrigerant respectively; M_{ac} and M_{r1} are masses of activated carbon and refrigerant adsorbed ($M_{r1} = x_1M_{ac}$) respectively; and T_1, T_2 are temperatures of adsorbent and adsorbate at point 1 and point 2.

Process 2: Isobaric Desorption (2 – 3)

The heat supplied in this process is used to heat up activated carbon and desorb the methanol in carbon is no longer a constant in this process, but decreases with heating. In other words, in this process, heat supplied does not only increase the generator's temperature, but also drives desorption of methanol out of carbon as desorption heat. Energy input can be calculated using Eq 3.2

$$Q_{2-3} = (C_{ac}M_{ac} + C_r\bar{M}_{r1})(T_g - T_{c1}) + \Delta x M_{ac} H_d \quad (2)$$

Where:

Q_{2-3} is heat supplied to heat up activated carbon and methanol, leading to desorption; \bar{M}_{r1} is the average mass of methanol, which can be evaluated approximated using $\bar{M}_{r1} = (M_{r2} + M_{r3}) / 2$; T_{c1}, T_g are temperature of point 2 and point 3; Δx is concentrated variation that is calculated by $\Delta x = x_2 - x_3$; H_d is treated as a constant for a given pair.

Process 3: Isosteric Cooling (3-4)

From point 3 to point 4 the process is called isosteric cooling because the generator is isolated, in which adsorbent is cooled down by cooling source (ambient air or water from cooling tower). In the meantime, system pressure drops and the resulting adsorbent's temperature decline. In this process, sensible heat is removed by an external cooling source and energy balance can be expressed as

$$Q_{3-4} = (C_{ac}M_{ac} + C_rM_{r3})(T_g - T_{c2}) \quad (3)$$

Where: Q_{3-4} is heat removed from the adsorbent and adsorbate by external cooling source; and T_g and T_{c2} are temperature of adsorbent at point 3 and point 4.

Process 4: Isobaric Adsorption (4-1)

Once the system pressure drops to the designed evaporated pressure, the evaporator is connected to the generator to initiate the adsorption process in which refrigeration effect is generated. Refrigeration output can be approximately calculated using Eq 3.4, in which the first term in the right hand of the equation represents the gross refrigeration capacity while the second term represents the refrigeration power loss due to its self-cooling from condensing temperature to evaporating temperature.

$$Q_r = (\Delta M_r L_o + C_r \Delta M_r)(T_{3i} - T_{4i}) \quad (4)$$

Where: Q_r is refrigeration output; L_o is latent of vaporisation of refrigerant (treated as a constant in ideal case analysis); ΔM_r is mass of liquid refrigerant that equates to $M_{r2} - M_{r3}$; and T_c

T_e are the values of condensing temperature and evaporation temperature respectively.

With the above analysis, for an ideal cycle, the refrigeration COP of the cycle can be evaluated using

$$COP = Q_r / (Q_{12} + Q_{23}) \quad (5)$$

3. EXPERIMENTAL ANALYSIS AND PROCEDURE

The aim and objective of this experiment is to confirm the workability of the activated carbon/Methanol pair. Also, to determine the efficiency which is the COP of the system using this same pair of refrigerant and adsorbent.

3.1 The Experiment System Set-up

The exploded and pictorial view of the experimental rig used for testing of the activated carbon- methanol pair are shown in **figure 3a and 3b**. The design calculations were carried out using mathematical analysis which was obtained by means of weight and energy balance in addition to the relations between temperature, pressure, concentration and enthalpy of the solution[14]. In the process of carrying out this analysis, the main assumptions considered were:

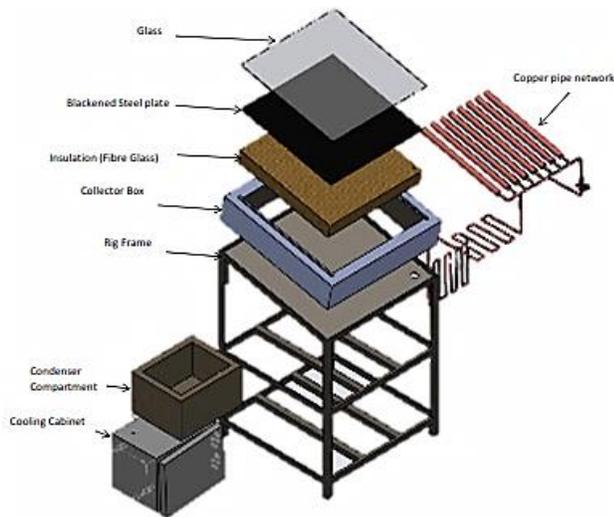


Fig. 3a schematic of the Experimental Rig



Fig. 3b pictorial view of the Experimental Rig

- All components are spatially isothermal and isobaric. Thus, the temperatures of the adsorbent material and of the system components do not vary spatially, but only temporally.
- The resistances to the methanol diffusion through the adsorbent bed and through the components have been neglected.
- The adsorbent particles have uniform shape, size and are uniformly distributed.
- The solid phase is in local thermal equilibrium with the gaseous phase in the adsorbent bed.
- The gaseous phase is treated as an ideal gas.
- All specific heats of the components and the heat transfer coefficients have been assumed to be constant.
- The thermal losses along the pipes have been neglected.

The major components and functions of the experimental rig are as follows:

• Solar Collector

This provides the system with the required heat needed for the adsorption process. The flat plate solar collector was used for this system due to its simplicity and low cost of construction. The flat plate collector was designed and constructed with the following component parts;

- glazing: a sheet of glass (about 2mm) was used, this helps to transmit the heat energy from the sun to the collector.
- black body: this component of the collector was added so as to help conduct a higher percentage of the transmitted heat to the reactor bed. The black body used was a steel sheet of about 1mm painted in black satin.
- insulation: the insulation was placed immediately below the reactor pipes and in-between the collector box. The material considered was fibre glass of about 150mm thickness.
- insulation box: this provides the insulated compartment for the whole collector. The external dimension was 1m square while the internal dimension was 0.8m.

• Condenser compartment

A 400mm by 400mm by 300mm concrete box with 50mm thickness was considered for holding up water that will be required for the cooling of the vapourised refrigerant during the adsorption and desorption process.

• Cooling cabinet

The cooling cabinet is a space where evaporation of water vapour and icing takes place. A well-insulated chest type cabinet was chosen to save material and simplify construction. The cabinet is large enough to contain five 1 litre containers and to avoid too much change of temperature during the day. The cabinet is insulated by 100 mm **Fibre glass**, and covered by 3mm white Perspex at the inside and outside. The dimensions are based on required capacity, convenience factors, and economical use of materials.

• The copper pipe network

The pipe network is of 3 sections;

- the reactor section: this is constructed with 8 series of 700mm long, two different dimensioned pipes welded end to end in concentric positions. And this

- section of the pipe is connected to the condenser part by a close/open valve of 25.4mm size.
- ii the condenser section: the dimension considered here was 25.4mm of about 3.0m long curved into 8loops of about 350mm long.

- iii the evaporator section: same as the condenser section design.

3.2 Experiment Procedure

The experiment was run according to the procedure as set out in table 1 and the explanation below:

Table 1: Procedure for operating the Ice-maker

Time	Valve	Process
9:00am – 11:30am	Valve closed	Adsorbent heated
11:30am – 5:00pm	Valve opened	Adsorbent heated and desorbing process
5:00pm – 7:00pm	Valve Closed and vent of collector opened	Condensation and cooling of refrigerant
7:00pm – 7:00am	Valve Opened	Evaporation, refrigerating effect. One cycle.

- The system was evacuated via the valve by means of a vacuum pump to a pressure of about -500mmHg which was maintained for about three consecutive days. This was done to ensure that the system could maintained vacuum state for this period.
- Then, the system was placed in a location where it could receive the maximum solar irradiation within the department project site.
- During each test period, the solar collector received solar radiation of average of about 500W/m² daily.
- Between the hours of 9:00am to 11:30am, the valve was closed to allow the adsorbent to be heated up so as to attain high pressure and temperature that could vaporise the adsorbate.
- Then between the hour of 11:30am and 5:00pm, the valve was open to allow the desorption of the adsorbate. Cooling water was also providing in the condenser chamber to allow cooling down of adsorbate before it gets to the evaporator section.
- When the desorption process was complete, the collector bow vents were open to allow ambient air to flow and start cooling the adsorber. And this is allowed to cool down until the pressure difference between the evaporator and adsorber was very low. This was done between the hour of 5:00pm and 7:00pm while the valve was closed.
- The cooling load of 5liters of water at temperature of 35°C was introduced in the cooling cabinet before the commencement of any adsorption processes.
- During evaporation of the vapour in the evaporator pipes, the cooling effect was expected to chill the water (load) placed in the cooling chamber. When adsorbent became saturated, a single intermittent cycle of adsorption was completed.
- The adsorber, condenser, ambient and evaporator temperatures were monitored. Also, solar irradiation received by the collector box was also monitored and recorded manually every 30mins.

4. RESULTS AND DISCUSSIONS

Sample results for the following day/night periods were chosen for analysis and performance evaluation of the system. Graphs for temperature versus time and solar insolation versus time were plotted on Ms-Excel. Table 2 shows the list of the selected dates that were considered for the performance analysis. Table 2 Selected date samples

Date (day night period)	
15/11/2012 – 16/11/2012	19/11/2012 – 20/11/2012
16/11/2012 – 17/11/2012	20/11/2012 – 21/11/2012
17/11/2012 – 18/11/2012	21/11/2012 – 22/11/2012
18/11/2012 – 19/11/2012	22/11/2012 – 23/11/2012

- **Analysis of the condenser temperature versus time over day/night period**

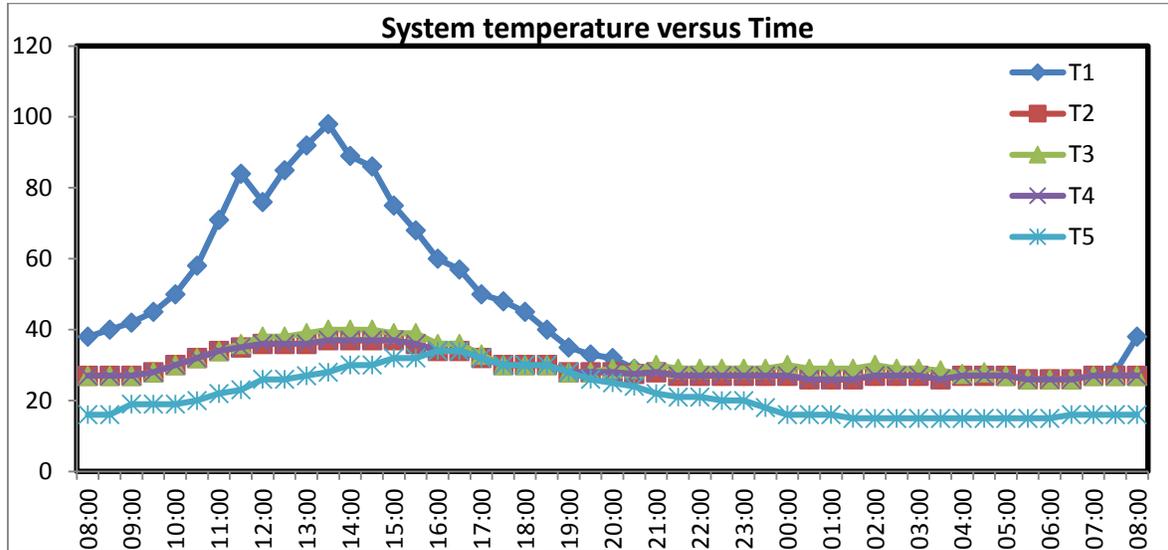
From figure 4, it can be seen that condensation start at 11:00am, the condenser maintained a temperature of 3°C above ambient temperature. Ambient temperatures during the methanol generation period ranged over 26 to 37°C, the condenser tube temperature increased with ambient temperature. Condensation occurred at an average temperature of 39°C

- **Analysis of activated carbon desorption mode**

Figure 4 also shows the adsorbent bed surface temperatures variations with time. Each test commenced at about 9:00 a.m. local time and ended when vapour desorption was completed at 6:00pm. The adsorbent tube surface temperatures closely followed the solar radiation pattern and the maximum temperature attained by the adsorber was 98°C at 2:00pm.

A steep rise in the adsorbent tube surface temperatures occurred at 9.00 a.m. and 12:00noon. At this stage, the heating resulted in pressurisation of the system an increasing in the temperature of the system, which was

more noticeable at around 2–3 hours from the start of heating. A significant drop in temperature also occurred between 2 p.m. and 7 p.m., when covers for the adsorber were removed at 5 p.m.



Where, T1 – collector temperature, T2 – Outside insulation temperature, T3 – Condenser Temperature, T4 – Ambient Temperature, T5 – Evaporator Temperature.

Figure 4: temperature versus time (15/11/2012 – 16/11/2012)

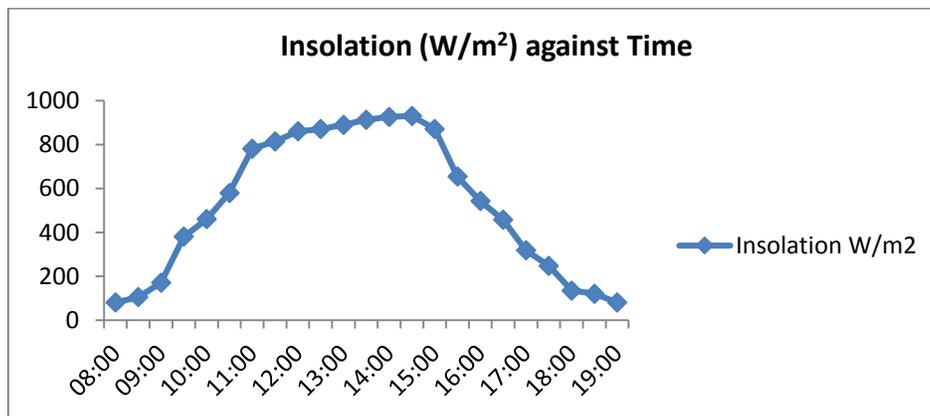


Figure 5: Insolation versus Time

• **Analysis of insolation available for the solar collector**

From figure 5, it will be noted that for this very day, which is a fairly clear day. The solar insolation rises steadily from 80W/m² at 8:00a.m. to 926W/m² at about 2:00p.m. at about this time, the temperature of the adsorber bed has risen to 98°C, which was the highest recorded for this day.

• **Analysis of methanol adsorption mode**

By opening the vent of the collector/adsorber at 5 p.m. local time signified the start of system cooling. The side vents were opened to facilitate natural convection cooling over the adsorber tubes. At 7 p.m., the valve connecting the adsorber to the evaporator was opened slightly (If the valve was fully opened, evaporation tends to occur on the top evaporator pipe, and this affected the cooling effect of the other evaporator pipes below) to start the adsorption of the vapour. The evaporator pipes' temperature

decreased gradually until it reached a minimum value of 15°C. Water load of 5 litres, initially at the temperature of 35°C was cooled to 18°C at the same time.

During the adsorption process, there was a slight increase (3°C) of the adsorber temperature, thus showing that the process was exothermic. Touching the adsorber pipes by hand showed that not all the pipes were warm. This was attributed to the packing arrangement of the activated carbon inside the pipes, meaning that methanol vapour might not flow around all the granules evenly. This could also be due to adsorption taking place predominantly at the beginning of the flow path. After the equilibrium state was reached, the adsorber temperature decreased to the nocturnal temperature.

During the day the evaporator temperature did not remain constant as was required. It rose from 18°C at 8:00a.m. to 28°C at 2:00pm. This was due to heat leaking into the cabinet and also from the piping connecting the evaporator to the rest of the system.

• Performance evaluation of the tested system

The performance of the adsorption cooling machine was evaluated in terms of useful heat delivered to the adsorber, thermal efficiency, the coefficient of performance, evaporation and condensation temperatures. The equations used by Anyanwu in previous studies were adopted [15].

• Useful heat delivered to the adsorber

The useful heat energy delivered to the adsorbent to desorb methanol vapour (Q_{ex}) is determined by the sum

of the sensible heat absorbed by the adsorbent, methanol and the latent heat of generation of methanol.

$$Q_{ex} = (M_{ac}C_{ac} + M_rC_{gr})\Delta T_g + M_m h_g \tag{6}$$

- Useful cooling produced (refrigerating effect) Q_{ref}

$$Q_{ref} = M_w \times C_w \times \Delta T_w \tag{7}$$

- The available condenser cooling capacity

$$Q_{cond} = M_r h_{fg} \tag{8}$$

- The total solar energy (Q_{gross}) delivered to the solar adsorber[16-18]

$$Q_{gross} = I \times A \times (\tau + \alpha_s) \tag{9}$$

- Co-efficient of performance (COP)

$$COP = \frac{Q_{ref}}{I} \tag{10}$$

- Sample of performance calculation (15/11/12 – 16/11/12)

$$I_{total} = 5297.4 \times 0.8 \times 0.945 = 4004.8 \text{ watts (from 9)}$$

$$\text{Hence, } I_{total} = 4004.8 \text{ (in watts)} \times 3600 = 14.4 \text{ MJ}$$

$$T_{initial} = 35^\circ C \quad T_{final} = 18^\circ C \quad C_p = 4.2 \text{ kJ/kg.k}$$

$$M_w = 5 \text{ kg (load mass)}$$

$$Q_{ref} = 5 \times 4.2 \times (35 - 18) = 357 \text{ KJ}$$

$$COP = \frac{Q_{ref}}{I} = \frac{357}{14417} = 0.025$$

Table 3: Summary of experimental results for selected days

DAY	I _{Total} (W/m ²)	I _{Total} (MJ)	T _{in}	T _{out}	Q _{ref} (kJ)	C.O.P	T _a	T _c	T _e
15/11/12 16/11/12	5297.4	14.4	35	18	357	0.025	30.9	29.5	21.7
16/11/12- 17/11/12	4112.4	14.8	35	18	357	0.024	30.3	28.2	23.3
17/11/12 - 18/11/12	5521.7	19.8	35	15	420	0.021	31	29.7	21.6
18/11/12 - 19/11/12	4447.8	16.0	35	18.5	346.5	0.022	31.5	28.5	21.9
19/11/12 - 20/11/12	2720.4	7.8	35	29	126	0.016	29.9	28.7	24
20/11/12 - 21/11/12	4820.8	17.4	35	18	357	0.021	30.8	29.4	21.7
21/11/12 - 22/11/12	4443.6	16.0	35	19	336	0.021	29.8	28.5	21.9
22/11/12 - 23/11/12	5532	19.9	35	14.5	430.5	0.022	30.6	29.6	21.2
23/11/12 - 24/11/12	3624	10.4	35	25	210	0.015	29.9	28.6	23

5. CONCLUSION

Apart from air and heat leaking into the system causing the ice-maker not to work properly, the ice-maker was designed; constructed; field tested and found to have worked reasonable well comparatively with the quantity of adsorbent and refrigerant used in the design.

Test results show that the ice-maker will be capable of producing ice if the solar collector is increased to about 1.6m² so as to permit larger quantity of adsorbent and refrigerant to be used, since the COP is relatively high when compared to early designs.

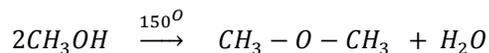
The low coefficient of performance of 0.025 was influenced by the following:

- Air leaking into the system
- The quantity of activated charcoal and methanol used (just about 3.79kg and 186ml respectively)
- The little quantity of methanol available for adsorption/desorption
- The effectiveness of activated carbon adsorption capability. During packing (brazing of the copper tubes) and testing, temperatures exceeded 120^oC. Temperatures above 120^oC render the activated carbon ineffective.
- The solar irradiation and the ambient temperature
- Heat loss when taking Temperature readings.

With the experiment carried out, the following conclusion may be reached:

- The intermittent solid-adsorption cooling cycle utilising the pair activated carbon-methanol works
- Temperature in vicinity of 110^oC are sufficient for appreciable desorption to occur.
- The adsorptive property of the activated carbon increases when it is in a dry state(after been heated repeated and allowed to cool)
- Low system pressures in general are critical to adsorption and desorption.
- Use of the on/off valves facilitates the separation of the adsorption process from that of desorption so that the volume of the methanol desorbed in any cycle of operation may be measured.

The results clearly demonstrate the suitability of the activated carbon-methanol pair for use in an intermittent solid adsorption cycle. Adsorbent temperature need to be kept below 150^oC because above this temperature the following reaction occurs:



This reaction is catalysed by the activated carbon. It is suspected that copper may also be a catalyst for this reaction and it may be necessary to avoid the transition metals which are catalysts for a variety of gas phase organic reactions. The Dimethyl ether product in the reaction has significantly different properties from methanol and introduces a non-condensable gas into the system, which causes the kinetics of the evaporation process to become extremely slow ^[17].

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