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Performance Evaluation of Intermittent Solid Adsorption Refrigeration System Running On Solar Energy

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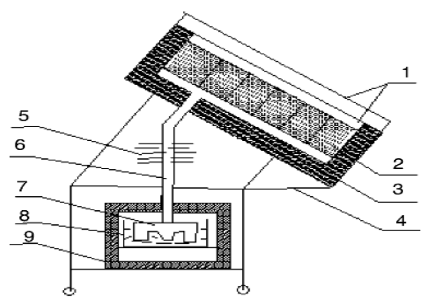
Abstract: International environment protection initiatives have led to the intensification of research efforts on development of ozone and global warming safe refrigeration technology. In recent years, increasing attention is being given to the use of waste heat and solar energy in energizing refrigerating 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. This paper is dedicated to the development of the thermally driven single effect, valveless adsorption refrigerator which uses activated carbon and methanol as adsorption pair driven by solar energy which is extremely portable. Where activated carbon and methanol is best suitable pair for the adsorption refrigeration process. Also refrigerant (methanol) has zero ozone depletion potential and very low global warming potential. Thus the refrigerator is eco-friendly. As there are no valves involved cost will be reduced. There are no moving parts involved in the system. Our goal is to develop an affordable, robust refrigerator that uses passive solar energy to maintain temperatures of water from 5°C to 10°C. COP of system is between 0.12 to 0.15. The refrigeration thus produced could be utilized for cooling water required for different domestic and industrial purposes. The mechanism, if extended, can produce further low temperatures also. Previous work on solar refrigerator has demonstrated the feasibility of the system. Work till date on such type of refrigerator shows various different pairs can be used as adsorbate-adsorbent for carrying out cooling effect but still so much scope is there for research. Because COP of such systems and temperature achieved by them is far away from the need of current era of refrigeration.

Keywords: adsorption, refrigeration cycle, refrigerator, solar energy

I. Introduction

The major attraction of solid adsorption refrigeration technology for cold production is that it can be powered entirely or partly by low grade energy such as solar energy, bio-energy etc. Its working fluids satisfy the Montreal protocol on ozone layer depletion and the Kyoto protocol on global warming. Furthermore, solar powered refrigeration based on adsorption cycle is simple, quiet in operation and adaptable to small, medium or large systems. Adsorption systems are invented with different focus. For one bed machine, simple structure and low cost are pursued. Several multi-bed systems are suggested to provide steady refrigeration and higher energy performance. One bed adsorption refrigerator is advantageous in simple structure and low initial cost. It can be used in applications when continuous cooling or higher cooling capacity is not required. Adsorption refrigeration system uses solid adsorbent beds to adsorb and desorb a refrigerant to obtain cooling effect. These solid adsorbent beds adsorb and desorb a refrigerant vapor in response to changes in the temperature of the adsorbent. Here adsorbent is an Activated carbon and the refrigerant used is methanol. The basic adsorption refrigeration system, commonly referred to as the adsorption heat pump loop, or an adsorption refrigeration circuit, it consists of four main components: a solid adsorbent bed, a condenser, and an evaporator ice-box. The solid adsorbent bed desorbs refrigerant when heated and adsorb refrigerant vapor when cooled. In this manner, the bed can be used as a thermal compressor to drive the refrigerant around the system to heat or cool a heat transfer fluid or to provide space heating or cooling. Thus in this system bed (of activated carbon) acts as compressor so as to drive refrigerant (methanol) similar to compressor in basic refrigerator. The refrigerant is desorbed from the bed as it is heated to drive the refrigerant out of the bed and the refrigerant vapor is conveyed to a condenser. In the condenser, the refrigerant vapor is cooled and condensed to liquid. The low pressure condensate passes to an evaporator where the low pressure condensate is heat exchanged with the process stream or space to be conditioned to vaporize the condensate. When further heating no longer produces desorbed refrigerant from the adsorbent bed, the bed is isolated and allowed to return to the adsorption conditions. When the adsorption conditions are established in the bed, the refrigerant vapor from the evaporator is reintroduced to the bed to complete the cycle. For the circulation of methanol in the system the whole system should be vaccumised.

Figure 1 shows schematic layout of a adsorption refrigeration system running on solar enegry. The solar refrigerator consists of an adsorbent bed (2), a condenser (5), an evaporator (7), water tank (8), insulation box (9) as well as connecting pipes. For this system, there are no any reservoirs, connecting valves and throttling valve, the structure of the system is very simple. The working principle of this no valve solar refrigerator is described as follows.



On a sunny day, the adsorbent bed absorbs solar radiation energy, which raises the temperature of adsorbent bed as well as the pressure of methanol in adsorbent bed. When the temperature of adsorbent reaches the desorption temperature, the refrigerant begins to evaporate and desorb from the bed. The desorbed refrigerant vapor will be condensed into liquid via the condenser and flows into the evaporator directly; this desorption process lasts until the temperature of adsorbent reaches the maximum desorption temperature. During night, when the temperature of the adsorbent bed reduces, the refrigerant vapor from the evaporator gets adsorbent back in the bed. During this adsorption process, the cooling effect is released from refrigerant evaporation, and the ice is formed in the water tank placed inside thermal insulated water box.

Figure 1: The sketch structure of the no valve solar ice maker: (1) cover plate, (2) adsorbent bed, (3) insulation materials,(4) frame, (5) condenser, (6) connecting pipe, (7) evaporator, (8) water tank, (9) insulation box.

Likely in a vapour compression system the adsorption refrigeration system also consists of a compressor, a condenser, and an evaporator but no throttle valve is used. However, in this system the compressor is replaced by a thermal compressor which is operated by heat instead of a mechanical energy. The vaporized refrigerant is adsorbed in the pores of the adsorbent in the reaction chamber i.e. adsorbent bed. Thus the operation of the adsorption cooling system depends on adsorption/desorption characteristics of the particular adsorbent/refrigerant pair. Due to the loading of the adsorbent, the thermal compressor is operated intermittently.

II. ADSORPTION REFRIGERATION CYCLE

Adsorption refrigeration system uses solid adsorbent beds to adsorb and desorb a refrigerant to obtain cooling effect. These solid adsorbent beds adsorb and desorb a refrigerant vapor in response to changes in the temperature of the adsorbent. The basic adsorption refrigeration system, commonly referred to as the adsorption heat pump loop, or an adsorption refrigeration circuit, usually consists of four main components: a solid adsorbent bed, a condenser, an expansion valve and an evaporator. The solid adsorbent bed desorbs refrigerant when heated and adsorb refrigerant vapor when cooled.

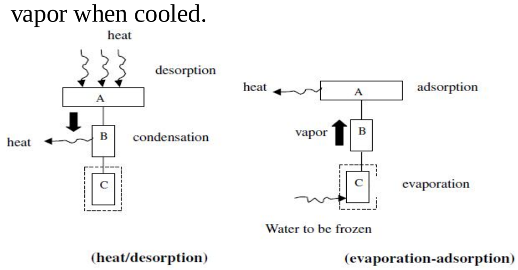


Figure 2: Adsorption (evaporation) and desorption (condensation) processes

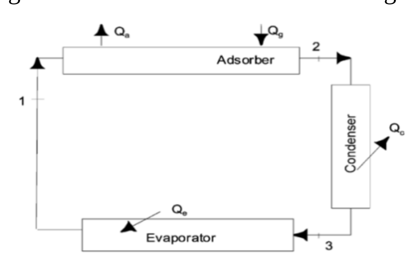


Figure 3: A Simple Adsorption Refrigerator

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Where,

Qg = The quantity of energy used to generate refrigerant vapour from the adsorbent during the generation process
Qa = The quantity of heat released by adsorbent
Qe = The quantity of heat transferred in the evaporator during refrigeration process
Qc = The quantity of heat dissipated by the hot refrigerant vapour to change to liquid form

III ANALYSIS OF ADSORPTION REFRIGERATION CYCLE

From the Clapeyron diagram, the total energy gained by the system during the heating period QT will be the sum of the energy QAB used to raise the temperature of the A.C+ methanol from point A to B and the energy QBD used for progressive heating of the A.C to point D and desorption of methanol.

QT = QAB + QB

QAB = (MA:C CpA:C + Cpm MmA) (TB - TA)

QBD = [MA:C CpA:C + Cpm { (MmA + MmD)/2 }] (TD - TB) + (MmA – MmD)H

The gross heat released during the cooling period Qe1 will be the energy of vaporization of methanol.

Qe1 = (MmA – MmD)L

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

Qe = Qe1 - Qe2

where Qe2 is the energy necessary for cooling the liquid adsorbate from the temperature at which it is condensed to the temperature at which it evaporates.

Qe2 = (MmA – MmD) Cpm (Tc - Te)

Qice1 is the energy required to cool water from TA to 0 ºC and to produce ice

Qice1 = M* (L* + Cpwater(TA - 0))

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

Qice = M* L*

Nomenclature

Cp	specific heat, kJ/kgK
H	heat of desorption, kJ/kg
L	latent heat of evaporation of the methanol, kJ/kg
M	mass, kg
Q	energy, kJ
T	temperature, ºC

Subscripts

c	condenser
e	evaporator
m	methanol
st	steel pieces
T	total

The cycle for adsorption refrigeration of AC-methanol can explain by Clapeyron diagram in (in P versus 1) /T.

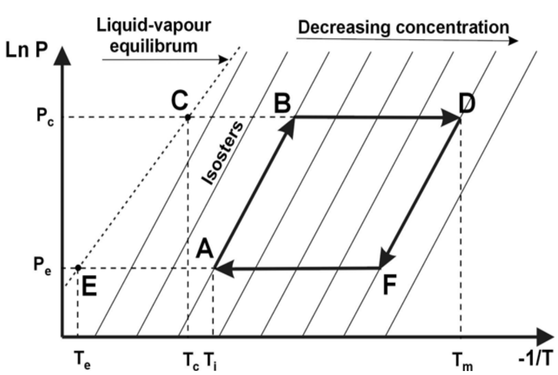

Figure 4: An ideal adsorption cooling cycle in the claperyon diagram.

The cycle is explained in detail in (Buchter F., 2001). We can summarize it in four stages:

Step 1: Isosteric heating (A→B):
The system temperature and pressure increase due to solar irradiance.

Step 2: Desorption + condensation (B→D):
Desorption of the methanol vapours contained in the activated carbon bed; condensation of the methanol steam in the condenser.

Step 3: Isosteric cooling (D→F):
Decrease of the period of sunshine; cooling of the activated carbon; decrease of the pressure and the temperature in the system.

Step 4: Adsorption + evaporation (F→A):
Evaporation of methanol contained in the evaporator; cooling of the cold cabinet; production of ice in the evaporator; re-adsorption of methanol steam by the activated carbon.

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Table 1: Main steps in solar powered adsorption ice-maker

Point shown in fig.	Time in day (approx)	Pressure	Developing process
A	Sunrise	Pe=Ps(Te)	End of adsorption
A-B	7a.m-10a.m		Isosteric heating of the adsorbent Pressurisation of the system
B			Onset of desorption
B-D	10a.m-4p.m	Pc=Ps(Tc)	Heating of the adsorbent Desorption and condensation of the refrigerant
			End of desorption
			Isosteric cooling of the adsorbent Depressurisation of the system
D-F	4p.m-7p.m	Pc=Ps(Tc)	Onset of adsorption Cooling of the adsorbent Evaporation and adsorption of the refrigerant
F		Pe=Ps(Te)	
F-A	7p.m. to 7a.m.		

IV. MATHEMATICAL MODEL OF THE SYSTEM

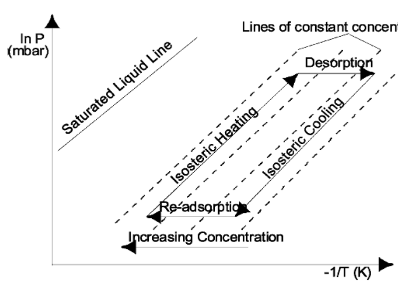

Figure 5: P-T-X diagram of an adsorption system showing the theoretical refrigeration cycle

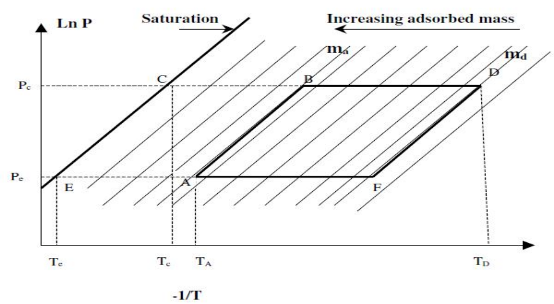

Figure 6: Clapeyron diagram (ln P versus -1/T) of ideal adsorption cycle

Tbdes = TEMPERATURE BEFORE DESORPTION
This temperature is taken before desorption process starts i.e. during morning session measured at adsorbent bed.
Tades = TEMPERATURE AFTER DESORPTION
This temperature is taken after desorption completes i.e at the end of day during evening session at adsorbent bed.
Ta = TEMPERATURE AT POINT A
This temperature is taken before afternoon session at the start of isosteric heating at adsorbent bed.
Tb = TEMPERATURE AT POINT B
This temperature is taken at afternoon time of the day and at the end of isosteric heating and start of desorption process at adsorbent bed.
Td = TEMPERATURE AT POINT D
This temperature is taken during evening session after desorption completes at adsorbent bed.

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Tcc = TEMPERATURE OF CONDENSATE
This is temp of condensate measured by measuring water/ice temperature at ice box during early morning session.
Tee = TEMPERATURE OF EVAPORATE
This is temperature of evaporate measured by measuring water/ice temperature at ice box during early morning session.

By Clapeyron theory the mass of methanol at point A and D is
Let, Mm = 1.3575 KG, mass of total methanol in system.
Mma = Mm*(75/100), mass of methanol at point A
= 1.3575*0.75
= 1.018125 KG
Mmd = Mm*(25/100), mass of methanol at point D
= 1.3575*0.25
= 0.339375 KG

V. OBSERVATIONS

DATE --------------------- TEMPERATURE (K)	1st 08/05/12	2nd 04/05/12	3rd 02/05/12	4th 30/04/12	5th 20/04/12	6th 18/04/12
Tbdes	30+273	29+273	31+273	30+273	30+273	31+273
Tades	50+273	50+273	48+273	49+273	51+273	51+273
Ta	30+273	29+273	31+273	30+273	30+273	31+273
Tb	38+273	37+273	39+273	38+273	39+273	40+273
Td	50+273	50+273	48+273	49+273	51+273	51+273
Tcc	15+273	16+273	15+273	15+273	18+273	19+273
Tee	14+273	15+273	14+273	14+273	17+273	17+273

VI. EXPERIMENTAL INVESTIGATIONS

As the system is a pilot project, experiments are carried out so as to check the exact working of the system. Following are some of the analysis made on the system.

VI. 1- VARIATION OF TEMPERATURE OF ADSORBENT BED WITH TIME:

The graph shown below is expected behavior of adsorbent bed. It is variation of temperature in the adsorbent bed because of incident solar radiations. Temperature in bed is directly proportional to the incident solar radiation. Effective solar radiations are available during period of 10 am to 3pm thus the temperature in bed during this period reaches to 100 ºC to 120 ºC. After 3 pm the temperature in bed gets lower and lower. Till 5.30 pm the temperature lowers to 20dgree c and desorption continues till that time. After this, temperature remains almost constant till 10.30 pm, now the adsorption of methanol starts. As adsorbent bed adsorbs vapours of methanol thus the temperature of adsorbent bed increases up to 60 ºC, approximately at midnight temperature is about 60 ºC – 70 ºC. After this the temperature again starts decreasing and exothermic reaction carry on. And now the bed will attain temperature of surrounding i.e. 25 °C.

VI. 2- VARIATION OF TEMPERATUTE OF WATER IN ICE-BOX WITH RESPECT TO TIME

The graph shown below is the expected graph of variation of temperature of water in ice-box with respect to time.

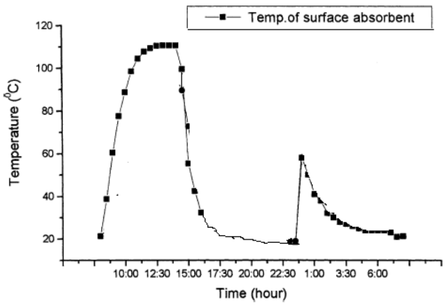

Figure 7: Variation of temperature of adsorbent bed with time

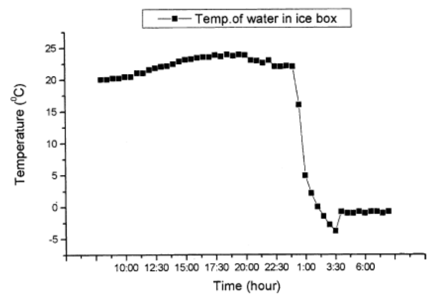

Figure 8: Variation of temperature of water in water box with time

VII. ANALYSIS OF OBSERVATIONS

The graph shows that during desorption process the temperature of water is 20 ºC, it remains constant till the de-sorption process ends. Desorption process has duration of about 7-8 hours. It ends approximately at 7 pm.

As the desorption ceases the adsorption process will start. After a particular timing the temperature of water decreases rapidly, that timing is critical timing of approximately about 11.30p.m. During this process methanol absorbs heat of water and thus methanol will evaporate and evaporated methanol will be adsorbed by AC. Thus ice is formed. And temperature of this ice will be -5 ºC at about 3.30 am. After 3.30 am temperature of water increases slightly to 0 ºC. It remains constant till approximately 7am. Now the ice produced can be removed from the box.

Table 2: Result table for analysis of the solid adsorption solar powered ice-maker

DATE ------------------- ANALYZED PARAMETER (ENERGY, KJ)	1st 08/05/12	2nd 04/05/12	3rd 02/05/12	4th 30/04/12	5th 20/04/12	6th 18/04/12
Qi	16280	16280	16280	16280	16280	16280
Qab	169.6612	169.6612	169.6612	169.6612	190.8688	190.8688
Qbd	268.6423	289.85	205.0194	247.4347	270.4111	249.2035
Qt	438.3035	459.5111	374.6805	417.0958	461.2799	440.0723
Qe1	785.9246	785.9246	785.9246	785.9246	785.9246	785.9246
Qe2	1.7688	1.7688	1.7688	1.7688	1.7688	3.5376
Qe	784.1558	784.1558	784.1558	784.1558	784.1558	782.3870
Qice1	628.5250	607.59	649.46	628.5250	628.5250	649.46
Qice	314.5000	314.5000	314.5000	314.5000	314.5000	314.5000

Table 3: Result table for performance estimates of the solid adsorption solar powered ice-maker

DATE -------------------- PERFORMANCE PARAMETER	1st 08/05/12	2nd 04/05/12	3rd 02/05/12	4th 30/04/12	5th 20/04/12	6th 18/04/12
$\eta 1$	0.0269	0.0282	0.0230	0.0256	0.0283	0.0270
$\eta 2$	0.8015	0.7748	0.8282	0.8015	0.8015	0.8301
COPcycle	1.7931	1.7103	2.0976	1.8843	1.7038	1.7859
COPsolar	0.0193	0.0193	0.0193	0.0193	0.0193	0.0193

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VIII.CONCLUSION

It is possible to consider that adsorption systems can be alternative to reduce the CO_2 emissions and electricity demand when they driven by waste heat or solar energy. Although, for a broader utilization the researches should continue aiming for improvements in heat transfer, reductions of manufacturing costs and for the formulation of new adsorbent compounds with enhanced adsorption capacity and improved heat and mass transfer properties. Because adsorption systems are generally poor thermal machines. The performance of adsorption systems depend strongly on the adsorption and condensation temperatures.

The following conclusions may be drawn from the foregoing solar powered solid adsorption ice-maker studies:-
-A solar powered solid adsorption icemaker using an activated carbon/methanol adsorbent pair has been successfully designed, constructed and tested
-The condenser and evaporator must necessarily be close to each other and to the collector since the system operates at low pressure, thus they are located directly under the collector such that the refrigerant flows into them by gravity.
-The adsorption bed (generator) is the heart of the system and it has the greatest effect on the performance of the system. A good design of the generator leads to smooth operation and better results, so more attention must be go to the design influence on the performance of the system.
-The ice produced can be used for various purposes such as in hospitals or for domestic use.
-The adsorption /desorption tests for activated carbon/methanol pair showed that there must be sufficient time to get the highest desorption of methanol, and the optimum time for that was found to be 5-10 hours.
The generation temperature must be over 100 °C in order to generate higher volume of methanol from activated carbon.
-COP of the system is 0.12, which is comparatively low but as the system works on solar energy it is eco-friendly system.
-From this study, one can conclude that the possibility of using nonpolluting materials and to save the energy involved in this sector are obviously the most important characteristics but simplicity, low maintenance, and the absence of noisy components are also very important features that make this type of system suitable for numerous other applications i.e. future scope of the project is such as air-conditioning in cars or food transportations or solar cooling with the use of: multi-bed systems.

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