Design Optimization and Simulation of an Ice Plant Working by Solar Adsorption Technology

H. A. Alamoudi and A.M. Abdel-Dayem

ABSTRACT

This research presents a design optimization of a solar adsorption ice plant using activated carbon and methanol as working pairs in the climate of Makkah to produce a ton of ice per day. The plant consists of six adsorption refrigeration units. Each unit has 72 separate cylindrical adsorbent beds connected with its own condenser, valve, and evaporator. The unit is heated by seven evacuated-tube collectors connected in parallel. Then the total number of collectors are 42 collectors. The beds are filled by estimated amount of 540 kg of activated carbon with 178 kg of methanol. Selection and dimensioning of each component were carried out based on previous recommended values. A mathematical model and simulation were developed to validate the system performance along the year. The results showed that plant could produce up to ton of ice daily along the year. The coefficient of performance can reach 0.9 with condenser and evaporator temperatures of 35°C and -5°C respectively. The performance of the system is greatly affected by ambient temperature than solar radiation. Therefore, the best performance and largest amount of ice was found in the winter season.

Keywords: Activated carbon/methanol, adsorption, refrigeration, solar energy.

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I. INTRODUCTION

Recently, there has been a high demand for electricity and hydrocarbon fuels that results from increased population density in the world and a large number of factories. Traditional refrigeration was one of the most important that causes the consumption of large amounts of fuel and electricity. That is due to the use of vapor pressure by compressors that operate on electricity. The combustion of fuels caused an increase in global warming in the universe and caused massive damage to nature and the Ozone layer. Therefore, it was necessary to use alternative energy instead of fuels and electricity. One of the most important of those natural resources was solar energy because it's sustainable and clean. It can be used in refrigeration and air conditioning units. The techniques of using solar energy in refrigeration systems are varied. One of those techniques was adsorption cooling. This technique was of utmost importance because it is cheap and easy to use and apply in addition to high efficiency. Besides, it is clean and safe and can be used in large cities and rural areas where electricity is not available. It can be manufactured in poor countries for use in storing and keeping foods, vaccines, and air conditioning. The modern designs showed remarkable development by [1] who presented an experimental study of a single bed adsorber-collector solar refrigerator that works with silica gel/water as

a adsorption pair. Results were obtained through experiments in the weather conditions of the Sfax region in Tunisia and it estimated of the highest *COP* solar was 0.078 and capacity was 777.96 in additional the lowest temperature reach it on amount 9 kg of water was 0 °C. [2] use lithium chloride (LiCl) with a solar ice maker and compared with pair activated carbon and methanol. Experiments were carried and ended up with a reaction between (LiCl) and ammonia at evaporation temperatures -10 °C and -5°C were adsorbed at temperatures between 25 to 35°C. The coefficient of performance (*COP*) was 0.47. The new composite got of the highest specific cooling capacity (SCC) compared to pair activated carbon and methanol. Reference [3] carried out experimental solar adsorption cooling system with activated carbon and methanol as working pair and compared with added copper filings. It gets to improve in *COP* 0.92 and temperature evaporator until -10 °C. Reference [4] designed solar adsorption cooling system driven by activated carbon and methanol and obtained of 3 kg of ice at -12 °C, 117 °C evaporator and generation temperature respectively and 0.12 *COP*. Reference [5] carried out tested on solar adsorption ice maker with activated carbon and methanol as working pair and obtained on 0.08 *COP* and produce 5 kg of ice at -13 °C evaporator temperature. Reference [6] presented a comparison between solar adsorption cooling system with silica gel-water and solar absorption cooling system with LiBr-H₂O utilized Compound Parabolic Concentrator (CPC)

and applied one vacuum valve innovative technology. the COP for adsorption system was 0.16 and 0.19 for absorption system. Reference [7] presented a numerical study to improve performance of solar adsorption refrigeration system with Activated carbon and ammonia as working pair utilized parabolic trough collector by simulated. The results indicated access COP to 0.43. Reference [8] investigated to solar adsorption cooling system consists of two-bed of silica gel-water as working pair utilized parabolic trough collector and heat storage tank. using a heat storage tank leads to an increased cooling of about 73.5MJ. Reference [9] investigated in carry out of experiment a solar adsorption cooling system with a working pair composite Zeolite 13X / CaCl_2 and water and utilized Six solar flat plate collectors with a total volume 12 m then got 0.12 to 0.24 COP . Reference [10] presented studying on the performance of solar adsorption cooling system with silica gel and water as a working pair and a compound parabolic collector on the climates of Perth and Amman. A TRNSYS (Transient System Simulation Software) program was used to study the system performance. the result show that COP was 0.491 in Perth and COP in Amman was 0.0467.

This research aims to design and performance analysis of a solar adsorption ice plant that produces one ton of ice per day. It considers the cycle structure used and its components. The materials and sizes of each component for manufacturing are addressed. Finally, it is studied the efficiency of the system and develop a mathematical model of the system to simulate the system performance based on the climate conditions of Makkah city.

II. ADSORPTION CYCLE

The idea of adsorption cooling is based on replacing the electric steam compressor system with an alternative thermal energy source from nature such as solar energy from the sun. Fig. 1 shows the basic components of adsorption cycle while Fig. 2 illustrates the system processes and can describe them as follows:

- Process (1-2) Isosteric heating: in the adsorbent bed, the adsorbent and adsorbate are exposed to heat and as a result, the adsorption process occurs, and the pressure rises. It should be closing the valves associated with the adsorbent bed.
- Process (2-3) Isobaric heating: After the adsorption process and when the adsorbent material reaches the required maximum temperature, the adsorbate is released to the condenser due to the high-pressure difference and it condenses there.
- Process (3-4) Isosteric cooling: In this process, the adsorbent bed temperature reduced and reach to evaporator pressure after down solar radiation and cooled it by ambient temperature.
- Process (4-1) Isobaric Cooling: The system pressure reaches the evaporator pressure, then the valve before the evaporator opened. The adsorbate in the evaporator absorbs the heat from the water and will be evaporated and absorbed by the adsorbent in the adsorbent bed [11].

Fig. 1. Schematic diagram of basic adsorption refrigeration.

Fig. 2. The diagram of adsorption system.

III. WORKING PAIR

Working pairs for adsorption systems are the main part to achieve adsorption technology and cannot work without it with refrigeration applications. Therefore, the choice of the working pair must be carefully chosen and the properties of which it can achieve the adsorption/desorption through its high ability high adaptive capacity at ambient temperature and low pressure for the adsorbent. Also, in case of high temperatures and high pressure has a lower adaptive capacity. The surface characteristics of the adsorbent materials are surface and polarity. To provide a large adsorption capacity a large and limited area must be utilized. The emergence of small pores between adsorption surfaces in large numbers is due to the foundation of a large inner surface with a limited size Internal. For an accurate distribution of pore size, adsorbents such as zeolite and active carbon particles can be designed and subsequently adjusted for specific separation [12].

In most experiments, the AC/ Methanol work pair is chosen due to their characteristics in addition to their low monetary value. By comparing seven pairs used in adsorption refrigeration equipment in several indicators, it was found that the performance of the system is affected by the physical and thermal properties of both working pairs of adsorbents and adsorbates. Activated Carbon Fiber/Methanol and Activated Carbon/Methanol can be reached maximal adsorption capacity by $(0.3406 \text{ kg kg}^{-1})$ and $(0.2565 \text{ kg kg}^{-1})$, respectively. After that it comes Activated Carbon/ Ethanol and Silica Gel/Water with capacity of $(0.2008 \text{ kg kg}^{-1})$ and $(0.1868 \text{ kg kg}^{-1})$, respectively. It can be used Silica Gel/Water for the purposes of air conditioning with coefficient of performance of about 0.3843 while the Active

Carbon/Methanol which is used for all cooling purposes and has high efficiency. The range of performance coefficient can be between 0.1726 and 0.843.

A. Adsorbent (Activated Carbon) Properties

The carbon can be produced from wood, coconut, nutshells, lignite. The specific surface of activated carbon is high between 400 and 2500 m² g⁻¹.

B. Adsorbate (Methanol) Properties

Methanol (CH₃OH) is an excellent refrigerant due to its high potential temperature when compared to water. Its

molecules are small and closely related and can be absorbed easily by microspores diameters smaller than 20 Å. It can be used in refrigeration applications with temperatures ranging from (-15 °C to 10 °C). One of its disadvantages is that it can decompose at temperatures above 150 °C [13].

IV. THE EXPERIENCES OF THE PUBLISHED LITERATURE

TABLE I: SOME PARAMETERS OF THE PUBLISHED LITERATURE EXPERIMENTS

No	Research	Collector	Working Pair	Cond. T°C	Eva. T°C	COP
1	[14]	flat plate	silica gel+water	NA	0	0.4-0.7
2	[15]	flat plate	carbon+methanol	30	-5	0.27
3	[16]	CPC	carbon+methanol	25	2	0.078
4	[17]	flat plate	carbon+methanol	42.5	-1	0.096
5	[18]	flat plate	carbon+methanol	NA	4	0.59
6	[2]	flat plate	lithium chloride+ammonia	35	-10	0.07-0.11
7	[19]	flat plate	carbon+methanol	NA	-	0.47
8	[20]	flat plate	carbon+methanol	31	-5	0.14
9	[21]	(ETC)	carbon+methanol	35	-2	0.12
10	[22]	flat plate	carbon+methanol	NA	0	0.3287
11	[23]	CPC	carbon+methanol	NA	0	0.1-0.36
12	[24]	flat plate	carbon+methanol	30	-4	0.123
13	[25]	flat plate	carbon+methanol	39	-5	0.09
14	[26]	flat plate	carbon+methanol	35	-4	0.12
15	[3]	flat plate	AC+COPer filling+methanol	35	-5/-10	0.17
16	[27]	flat plate	carbon+methanol	30	-3	0.92
17	[28]	heat source	Calcium chloride+ammonia	NA	-3	0.73
18	[29]	PTC	CaCl ₂ +AC+ammonia	30	-3	0.13
19	[5]	flat plate	carbon methanol	25	-13/-5	0.21
20	[4]	flat plate	granular carbon+methanol	25	-12	0.08

V. CONSIDERED SELECTION OF SOLAR ICE PLANT

The researchers' experiments presented in Table I reviewed the previous researchers' experiment parameters. After the comparison, the four best experiments published were selected in terms of evaporator temperatures with COP due they are the most important parameters to choose the ice production system design. The chart in Fig. 3 shows that the experiments of researchers [2] and [3] achieve the same temperature -10 °C but they take a different COP by 0.47 and 0.92, respectively. As for the experiment of the researcher [4] obtained -12 °C and COP 0.12 that a good evaporator temperature but the COP is low. The best evaporator temperature was the experiment of the researcher [5], where he obtained -13 °C at COP 0.08 and that consider the lowest COP among selected published literature.

Deduce from Fig. 3 that demonstrate the four selected experiments in terms of evaporator temperature, which were focused on because of the proposed system's goal of producing ice as well as the coefficient of performance through which it indicates the efficiency of the system. Three of the four selected experiments used activated carbon and methanol as working pairs so it will be chosen the same working pairs of activated carbon and methanol in the proposal ice plant design. Therefore, it can choose [3] design to conduct experiments and study the performance of the proposed solar adsorption ice plant system because has of high coefficient of performance and the low-temperature evaporator.

Fig. 3. The relation between the COP and evaporator temperature in the selected published literature.

Description of The Proposed Solar Adsorption Ice Plant

The suggested model is selected from [3] that we referred to previously which was on a refrigeration system that operates with the adsorption technology powered by solar energy with a working pair of activated carbon and methanol. The system consists of two circuits as shown in Fig. 4 the solar system cycle and the adsorption refrigeration cycle. The parts of the solar system were

1. Solar collector.
2. A circulation water pump.
3. The adsorbent bed.
4. The pipe loop that links up the parts of the solar collector circuit which holds the distilled water.

Fig. 4. Schematic diagram of selected system.

While the second cycle contains the condenser, an expansion valve and an evaporator which is the adsorption refrigeration system circuit operating with the working pair of activated carbon and methanol.

VI. DESIGN OF THE CONSIDERED SYSTEM

A. Study of Generation Temperature (T_g) Versus COP

The generation temperature (T_g) is related to the COP in solar ice maker systems that use the activated carbon and methanol working pair, so it was highlighted to study the relationship between them and choose the appropriate solar collector based on the generation temperature. Fig. 5 shows the relationship between COP and T_g among a set of trials presented in Table I. The lowest values of the COP were for [5] (0.08), [4] (0.12), [20] (0.14) and [26] (0.017) at T_g 93 °C, 88 °C, 105 °C and 100 °C, respectively. The medium values of COP were for [15] (0.27) at T_g 110 °C and [22] (0.36) at T_g 100 °C. The high values of COP were for [2] (0.47), [30] (0.51), [31] (0.59) at T_g 80, 85 and 127 °C, respectively. The highest COP was for [27] at T_g 95 °C. The relation between T_g and COP complicated and depends on the condition surrounding the system but can be considered of range of T_g between (80 to 95) is the suitable temperature generation for the adsorption solar system.

Fig. 5. The related between cop vs generation temperature in the published that used ac and methanol as a working pair.

TABLE II: COMPARING THE PRESENT RESULTS FOR [30] PUBLISHER

Reference [30]	Generation T °C	COP
(4)	84.9	0.51
(3)	86.6	0.48
(1)	93.6	0.44
(2)	100	0.32

Also, the Table II shows varying COP with T_g in the presentation of results for [28] which illustrated up of the COP with a reduced of T_g in the same conditions for the experimental while was the COP 0.32 at T_g 100 °C and reach until 0.51 at 85 °C T_g . It is concluded from Figure 10 and Table II that the appropriate generation temperature for methanol evaporation is between 80-95 °C so the solar collector will be chosen based on the mentioned temperatures.

B. Selection of Appropriate Solar Collector

There are many commercial solar collectors available in the market, so when choosing the type of solar collector suitable for solar adsorption refrigeration. First must be determined the required temperature for the system. Secondly, studying the efficiency of solar collectors in operating and climatic conditions. Reference [32] presented a

many of different types and specifications of solar collectors in Table III and applied the Eq. (1) for getting the mean efficiency of each hour per day (η) [33]:

$$\eta = \eta_0 \frac{(K_{\theta b}(\theta) G_{b,t} + K_{\theta d} G_{d,t})}{G_t} - a_1 \frac{(T_m - T_a)}{G_t} - a_2 \frac{(T_m - T_a)^2}{G_t} \quad (1)$$

where η_0 [-] is the zero-loss collector efficiency, a_1 [$W/m^2 K^2$] is the heat loss coefficient, a_2 [$W/m^2 K^2$] is the temperature dependence of the heat loss coefficient, G_t [W/m^2] is the sum hourly global solar radiation on surface tilted long the year, $G_{b,t}$ [W/m^2] the sum beam radiation and $G_{d,t}$ [W/m^2] the sum diffuse solar radiation on a surface tilted long the year, T_m [K] is the mean heating temperature, T_a [K] the ambient temperature, $K_{\theta d}(\theta)$ [-] is the diffuse incident angle modifier, and $K_{\theta b}(\theta)$ [-] is the direct incident angle modifier for the angle of incidence, θ .

The Eq. (2). [32] calculated the direct incident angle modifier $K_{\theta d}(\theta)$ without the $\cos \theta$ for PTC if assumed the diffuse incident modifier, $K_{\theta b}(\theta)$ low concentration ratio (C) equal 1/ C .

$$K_{\Theta b}(\theta) = K_{\Theta L}(\theta_L) K_{\Theta T}(\theta_T) = \left(1 + \frac{(b_{1L} \theta_L + b_{2L} \theta_L^2)}{\cos \theta_L}\right) \left(1 + \frac{(b_{1T} \theta_T + b_{2T} \theta_T^2)}{\cos \theta_T}\right) \quad (2)$$

TABLE III: PROPERTIES OF THE COLLECTOR

Type of Collector	FPC-1	FPC-2	ETC	CPC	PTC-1	PTC-2	PTC-3
Specific Costs	Standard	Standard	Standard	Standard	Standard	Low cost	Low cost
Aperture width [m]	2.38*1.06	2.38*1.06	1.45*1.64	2.43*1.62	2.3	1.7	1.2
τ_0 [-]	0.776	0.791	0.745	0.644	0.6931	0.5897	0.68
a_1 [W/(m ² K)]	4.14	3.94	2.007	0.749	0.4755	0.9317	0.4
a_2 [W/(m ² K ²)	0.0145	0.0122	0.005	0.005	0.003128	0	0.0015
$K_{\Theta d}$ [-]	0.84	0.876	0.85[132]	0.54[133]	0.070 [134]	0.048[134]	0.073[134]
b_{1L} [-]	1.46E03	1.00E03	1.37E03	1.14E03	3.18E04	3.06E03	2.20E04
b_{2L} [-]	4.50E07	3.00E07	1.10E05	8.93E06	3.99E05	7.40E06	3.83E05
b_{1T} [-]	0	0	8.315E03	9.948E0	0	0	0
b_{2T} [-]	0	0	8.896E05	9.530E06	0	0	0
Tracking Mode	None	None	None	None	1-axis	1-axis	1-axis
Axis	None	None	None	None	1-axis	1-axis	1-axis
Orientation	South	South	South	South	N-S	N-S	N-S
The Efficiency	0.5485	0.5885	0.7235	0.5005	0.4813	0.3702	0.4759

Table III contained measured data by a weather station of the University in a horizontal position during the period 2015 for Makkah city included on horizontal solar radiation and mean ambient temperature. It used the MATLAB program to find the efficiency for (FPC-1, FPC-2, CPC, ETC) by using the sum of solar radiation on surfaces tilted (latitude of Makkah city) 21.5 per hour day length of the year on the variable is $[\Delta T/Gt]$. For the collectors (PTC-1, PTC-2, PTC-3) to find the efficiency for them it used the sum of solar radiation on track surface one-axis (N-S) for Makkah city per hour day length of the year.

TABLE IV: THE MEAN PARAMETERS USED FOR REQUIRED OF EFFICIENCY

Parameters	Value	Units
The Hour of the Day	12.25	H
Gd, T, Annual	2742.7	[Kwh/M2]
Gb, T, Annual	4612.9	[Kwh/M2]
Gt, Annual	7405.6	[Kwh/M2]
Gd, T, (Tracking), Annual	912.55	[Kwh/M2]
Gb (Tracking), T, Annual	646.28	[Kwh/M2]
Gt (Tracking), Annual	251.26	[Kwh/M2]
Angle Tilted	21.5	°
Longitude	39.5	°
Latitude	21.5	°
Tm	85	°C
Ta	31.06	°C
Location	Makkah	Ksa

After making a comparison of the solar collector data presented in Table IV by applying Eq. 1 and 2 in addition to the spatial conditions presented in Table III. figure 7 shows the results of comparison of the collectors where the PTC-2, PTC-3 and PTC-1 obtained a lowest efficiency estimated at 0.4813 ,0.3702 and 0.4759, respectively. The CPC got an efficiency of 0.50 followed by the PFC-1 and PFC-2 0.5485 and 0.5885, respectively. The highest efficiency was for the ETC collector by 0.7235 and it is the suitable collector for solar adsorption ice plant.

Fig. 7. The Efficiency Comparison of Solar Collectors.

VII. DESIGN OF SOLAR ICE PLAN COMPONENTS

A. Solar Collector

It is used to collect the radiation of the sun to heat the fluid that used to rises temperature in the adsorbent bed. It has been chosen from [32]. It is an evacuated tube collector with aperture width (1.45×1.64 mm) and has an efficiency of 0.745 oriented to the south 21.5 (latitude of Makkah). The collected energy from one collector in climate in Makkah on December 21 is 31311 kJ/day. Reference [34] designed a solar adsorption ice maker produces 35 kg of ice by collecting value energy of 46200 kJ by 6 m² of solar collector area. So, it can conclude that to produce a ton of ice it estimates to needs 42 collectors to achieve our goal. For simple manufacturing, maintenance, and operation the plant can be divided into 6 devices each one produces about 170 kg of ice daily. The one device contains seven or more collectors constitute two arrays.

B. Circulation Pump

It is a pump that controls the fluid flow within pipe from the Sun Maxx Solar company model of (UniMaxx-PLUS-SC500-AC-V3). The flow meter is up to 10 gpm with pressure gauge up to 6 bars. It works with temperature fluid reached to 160 °C with power consumption of 0.1 HP.

C. Adsorbent Bed

The adsorbent bed was chosen from [29] that carried out an experiment on a solar adsorption ice maker and produced 30 kg of ice by utilization 4 cylinders of adsorbent bed filled by CaCl_2 and carbon with length is 1800 mm and the diameter of each one 159 mm inside it seven fins tube filled with 30 kg of adsorbent heated by oil from 36 m^2 of solar PTC [29]. Therefore, to produce about 170 kg of ice so it came up with a design configured of 72 cylinders adsorbent beds parallel to avoid becoming a pressure vessel. Every adsorbent bed with a diameter of 159 mm and a length of 1800 mm as shown in Fig. 8. Each cylinder adsorbent consists of seven fin tubes full of activated carbon. The total mass of activated carbon is 540 kg in 704 fins.

Fig. 8. Schematic of adsorbent bed.

D. Condenser

The air-cooled condenser was designed from the *COP* per tubes with aluminum fins and is cooled by natural convection surrounding air. Its function is to Condensate the methanol and converts it from gas to liquid case. the diameter of tubes of condenser is 16 mm and the total surface area is 44 m^2 . The vertical condenser is designed as convenient for the system.

E. The Evaporator and Moulds of Ice

A design of the evaporator is different from the other systems. It is configured of twelve molds made of stainless-steel plate with dimensions of (24 cm $\times$ 15 cm $\times$ 70 cm) to hold 25 kg of ice. That variation of dimensions is due to easy removing of ice. The molds are surrounded by grade aluminum evaporator surface area of 5.3 m^2 capacity is 300 liters of water. The evaporator is placed inside an insulated covered container.

VIII. DESCRIPTION AND OPERATION SYSTEM

The system of solar adsorption ice plant divides to six units, each unit will produce about 170 kg per day of ice to become the sum daily production of about a ton of ice. Essentially, the unit consists of seven solar evacuated tube collectors parallel dimensions are (1.45 m $\times$ 1.64 m). There are 72 parallel cylinders adsorbent beds with a diameter of 159 mm and a length of 1800 mm consist of seven fins tubes filled with 540 kg of activated carbon and 178 kg of methanol. Also, the units contain on a condensers with 44 m^2 connected to an expansion valve. In the last part of the unit, the evaporator by 5.3 m^2 within the insulated container surroundings by twelve molds ice capacity is 300 liters of water. In the beginning of operation, the collectors will absorb the heat from the sunshine and transfer the heat to the oil fluid. The beds will receive the heat from the oil by a

circulation pump to make the adsorption and desorption process in a daytime. At night and after sunset, the valve (1) will open, and the activated carbon releases the heat, and the methanol will leave to the condenser for condensation. The methanol will convert from gas to liquid case after that by the expansion valve is converted from high pressure to low pressure within the evaporator to pull heat from water to methanol and reduce the temperature of water under 0 $^{\circ}\text{C}$ then the water will convert to the ice. In the last process in the morning, valve (2) will open, and the methanol will vaporize and back at the adsorbent bed.

IX. THERMAL VALUES CALCULATOR

Fig. 9. The basic adsorption refrigeration cycle diagram.

Fig. 9 shows the basic thermal processes in an adsorption cycle. It will get known with the equations for each process as follows:

A. The Collected Heat Energy from Collectors

$$Q_g = (It/3.6) A_c \eta_c \quad (3)$$

A_c : area of the collector;

It : total hourly global solar radiation on surface tilted;

η_c : Efficiency of The Collectors.

B. Isosteric Heating Process Point of (1-2)

$$Q_h = \int_{T_{g2}}^{T_{g1}} C_{ac}(T) M_{ac} dT + \int_{T_{g2}}^{T_{g1}} C_{Lc}(T) M_{ac} x_{a2} dT + \int_{T_{g2}}^{T_{g1}} C_{madb}(T) M_{madb} dT \quad (4)$$

$C_{ac}(T)$: is the specific heat capacity of carbon;

$C_{Lc}(T)$: is the specific heat capacity of methanol;

$C_{madb}(T)$: is the specific heat of methanol in the adsorbent bed;

M_{ac} , $M_{acx_{a2}}$ and M_{madb} : are the mass of carbon, liquid methanol, methanol of the adsorbent bed, respectively;

x_{a2} : is the adsorption quantity of the adsorbent bed at the end of the adsorption process at temperature T_{a2} .

C. Isobaric Desorption Process Point of (2-3)

$$Q_d = \int_{T_{g1}}^{T_{g2}} C_{ac}(T) M_{ac} dT + \int_{T_{g1}}^{T_{g2}} C_{Lc}(T) M_{ac} x_{a2} dT + \int_{T_{g1}}^{T_{g2}} C_{madb}(T) M_{madb} dT - \sum_{T_{g1}}^{T_{g2}} M_{ac} h_d \frac{dx}{dt} dt \quad (5)$$

dx : is negative in the desorption process;

h_d : is desorption heat;

x : is the adsorption quantity of the adsorbent bed.

From this equation with equations (3), (4), and (5) it can be found $Tg2$.

- Generated energy must be equal or more than the esorption heat with the isosteric heat and expressed as:

$$Qg = Qh + Qd \quad (6)$$

D. Isosteric Cooling Process Point of (3-4)

$$Qc = \int_{Tg1}^{Tg2} C_{ac}(T)M_{ac} dT + \int_{Tg1}^{Tg2} C_{Lc}(T)M_{ac}x_{a2} dT + \int_{Tg1}^{Tg2} C_{madb}(T)M_{madb} dT \quad (7)$$

$xg2$: is the adsorption quantity at the end of the desorption at temperature $Tg2$ adsorbent.

E. Isobaric Adsorption Process point of (4-1)

$$Qad = \int_{Ta1}^{Ta2} C_{ac}(T)M_{ac} dT + \int_{Ta1}^{Ta2} C_{Lc}(T)M_{ac}x_{a2} dT + \int_{Ta1}^{Ta2} C_{madb}(T)M_{madb} dT + \sum_{Ta1}^{Ta2} M_{ac} h_d \frac{dx}{dt} dt - \int_{Tg1}^{Tg2} C_{pc}(T)M_{ac}xd(T - T_e) \quad (8)$$

$Cac(T)$: is the specific heat at constant pressure of the gaseous working fluid.

hd : is the adsorption heat.

F. Cooling Power from the Evaporation Heat of the Refrigerant

$$Q_{ref} = M_{ac} \Delta x L \quad (9)$$

G. The Heat Released in The Condensation Process

$$Q_{cond} = M_{ac} \Delta x L + \int_{Tg1}^{Tg2} C_{pc}(T)M_{ac}xd(T - T_c) \quad (10)$$

H. The Sensible Heat Released to The Surrounding the Liquid Refrigerant Dropped From Tc To the Evaporation Temperature Te

$$Q_{evas} = \int_{Tc}^{Te} C_{Lc}(T)M_{ac} \Delta x dT \quad (11)$$

I. The Coefficient of Performance (COP)

$$COP = \frac{Q_{ref} - Q_{evas}}{Qg} \quad (12)$$

J. Mass of Ice Production Daily (Mice)

$$M_{ice} = \frac{Q_{ref}}{C_w(T_w - 273) + L_f + C_{ice}(273 - T_{ev})} \quad (13)$$

C_w : is specific heat of water. T_w is temperature of water.

L_f : is latent heat of ice fusion. C_{ice} is specific heat of ice.

K. Adsorption Ratio (x) Equation

$$x = x_0 \exp \left[-K \left(\frac{T}{T_{sat}} - 1 \right)^n \right] \quad (14)$$

x_0 : is the maximum adsorption rate;

K : is a coefficient determined by the adsorbent structure and is unrelated to the refrigerant;

n : is reflects the distribution of the pore diameter of the adsorbent;

T_{sat} : is the Tc or Te ; it depends to the process pressure.

In the Calculations, $Tg1$ is Correlated with Tc , and Te is Correlated with $Ta2$. D-A Equation is solved on both Parties of $xg2$.

$$Tg1 = Ta2 \frac{T_c}{T_e} \quad (15)$$

In the Calculations, $Tg2$ is Correlated with Tc , and Te is Correlated with $Ta1$. D-A Equation is solved on Both parties of $xg2$.

$$Ta1 = Tg2 \frac{T_e}{T_c} \quad (16)$$

L. The Equations for The Properties Used in The Simulation

- CLc - Specific heat of liquid Methanol:

$$C_{Lc} = 0.78019 + 0.005862T \quad (17)$$

- Cpc - Specific heat of gas Methanol:

$$C_{PC} = 0.66 + 0.221 \times 10^{-2}T + 0.807 \times 10^{-6}T^2 - 0.89 \times 10^{-9}T^3 \quad (18)$$

- Cac - Specific heat of Activated Carbon:

$$C_{ca} = 0.805 + 0.00211T \quad (19)$$

- L - Latent heat of vaporization of Methanol (heat of condensation):

$$L = 1252.43 - 1.59593T - 0.00881551T^2 \quad (20)$$

In the equation of vaporization heat, the unit of the temperature is °C, and for other equations the unit for the temperature is K.

This program simulates the COP in all days of year, we should select the day and input the mass of activated carbon, then it will be calculating the COP and the thermal values of the system.

X. RESULTS AND DISCUSSION

A simulation program was made on (MATLAB) in a climate of Mecca, KSA latitude (21.5 South) on a solar adsorption ice plant system consisting of seven solar evacuated tube collectors that were selected in the previous chapter and 72 cylinders adsorbent bed each one contained 7.5 kg of activated carbon (AC) and 178 kg of methanol inside the evaporator. The evaporator containers contained 12 molds with a capacity of 300 liters of water for the purpose of freezing them and turning them into ice. The basic equations in solar adsorption systems were applied to the system throughout the days of the year 2015 on the data of solar radiation measured on the horizontal.

A. Solar Radiation

Fig.10. Total daily horizontal solar radiation on a surface per m².

Fig. 10 presented the sum values of solar radiation data (I_t) for all days of the year. The lowest values of radiation appeared in the winter season and gradually increased in the spring and autumn seasons and peaked in the summer season. The average daily radiation was (20289 Wh/m²) and the lowest value of radiation recorded was (11574 Wh/m²) on 10 December at the beginning of the winter season and it may be due to clouds or rain, while the largest value of radiation was (24690 Wh/m²) on 30 March at the beginning of the fall season that might back to clear of sky.

B. Generated Energy

Fig.11. Generated energies long the year.

Fig. 11 illustrated the generated energy (Q_g) resultant from the sun by twelve solar collectors every day of the year. The energy generated is affected by solar radiation were becomes lower in the winter season and higher in the summer. The mean daily of generating energy is (251610 kJ) and the minimum generated energy is (143530 kJ) while the maximum generated energy is (306190 kJ).

C. Generation Temperature and Ambient Temperature

Fig. 12. Cycle temperature, ambient temp. With maximum temp. In year days.

Fig.12 shows the variation of ambient temperature (T_{a2}) and generation temperature (T_{g2}). The range of (T_{a2}) is from 20.5 °C to 35.2 °C and the average temperature is 29 °C. While the minimum temperature of (T_{g2}) is 79 °C and the

average temperature is 118.8°C. The maximum temperature was 148 °C that convenient for methanol where if the degree exceeds 150 °C that will cause to the decomposition of the methanol.

D. The Coefficient of Performance (COP)

Fig. 13. COP values in year days.

Fig.13 shows the coefficient of performance (COP) of the adsorption solar ice plant whole of the year. The largest value was 0.9 and the lowest value was 0.3, while the average performance was 0.43. The coefficient of performance changes during the periods of the year due to the difference in the amount of radiation falling on the surface of the solar collector as well as the ambient temperatures.

E. Daily Ice Production

Fig. 14. The daily ice production amount.

The amount of ice produced solar adsorption ice plant through 6 units ranges from 1051 kg to 1684 kg and the mean amount of mass of ice is 1302 kg daily as shown in Fig. 14. The amount of ice is affected by sensible heat in the evaporator (Q_{ref}). During the summer season, the amount of ice production decreases, and the amount increases in the winter, autumn, and spring seasons.

The results of the program, which are visible in the previous figures, show the effect of higher temperatures in the summer season and the amount of solar radiation on (COP). It was noticed when increase (Q_g) it will reduce the (COP). Also, the effect of the winter season and lower temperatures and the amount of radiation positively on the rise (COP). Moreover, the effect of the ambient temperature on the mass of ice (M_{ice}) where an increased amount of (M_{ice}) in the winter season and decrease of (M_{ice}) in summer season due variation of ambient temperature.

TABLE V: THE VALUE OF PARAMETRS OF THE SYSTEM

Parameters	Min	Mean	Max	Unit
Qg	143530	251610	306190	kJ
Qh	48601	48945	49567	kJ
Qd	94297	202670	256990	kJ
Qc	40411	47219	52408	kJ
Qad	190660	220670	255920	kJ
Qcond	77401	94724	120820	kJ
Qevas	6167	7640	9879	kJ
Qeref	78716	97508	126100	kJ
Lf	---	334	---	kJ/kg
Ta2	20.5	29	35.2	°C
Tg2	79	118.8	148	°C
COP	0.3	0.43	0.9	---
Mice	1051	1302	1684	kg

XI. VALIDATION OF PREDICTED RESULTS WITH THE PREVIOUSLY PUBLISHED LITERATURE

TABLE VI: COMPARISON PRESENT SIMULATION WITH PREVIOUS PUBLISHED LITERATURE

Publishers	Td (°C)	Tc (°C)	Te (°C)	COP
[2]	80	35	-10	0.47
Present work	86	35	-10	0.77
[3]	89	35	-10	0.92
present work	89	35	-10	0.70
[4]	88	25	-12	0.12
present work	88	25	-12	0.56
[5]	93	25	-13	0.08
present work	93	25	-13	0.51

Table VI Compared *COP* for this work with the four selected experiments in the previous chapter under the same condition parameters (as *Td*, *Tc*, and *Te*) to ensure simulation program validation. The present work got 0.77 *COP* compared with [2] in all parameters (35°C *Tc*, -10°C *Te*, 80°C *Td*) the system couldn't reach to *Td* with low evaporator temperature *Te* (-10) due needs to generation temperature (*Td*) bigger 86°C. Another experiment for [3] was Compared with the work presented in the same operating conditions (35°C *Tc*, -10°C *Te*, 89°C *Td*) and obtained 0.7 *COP*. [4] has a different condition (25°C *Tc*, -12°C *Te*, 88°C *Td*) and after editing the program to same condition obtained to 0.56 *COP*. Finally, the experiment was for [5] and obtained our present work on 0.51 *COP* in condition of (25°C *Tc*, -13°C *Te*, 93°C *Td*). The variation of the results among of experiments is clear in Fig. 15 and that due to different systems used.

Fig. 15. The validation of COP present work with others experiments.

XII. INVESTIGATION OF THE EFFECT OF AMBIENT TEMPERATURE ON *COP* AND DIP

Fig. 16. The variation of COP with ambient temperature.

Fig. 16 shows the change in the minimum, average and maximum *COP* value with the change in ambient temperature (*Ta*), and the system was evaluated on (*Ta*) (20, 5, 35, 45, and 50 °C) considering the lowest ambient temperature in a weather Mecca is 20.5°C and the highest temperature is near 50 °C where a decrease in *COP* is shown with a rise (*Ta*). The lower (*Ta*), the higher the *COP* value. The system obtained to the maximum *COP* 0.95, 0.83, 0.6, 0.42, 0.35 at (*Ta*) 20.5 °C, 25 °C, 35 °C, 45 °C, 50 °C, respectively. Fig. 17 reveals the stability of the value of the daily ice mass throughout the year with stability in the ambient temperature (*Ta*), and the system was evaluated on different temperatures (*Ta*) (as 20.5 °C, 25 °C, 35 °C, 45 °C, 50 °C) in weather conditions in Mecca. The amount of snow did not change throughout the year with the same (*Ta*), as it obtained the amount of mass ice 1687, 1470, 1060, 745 and 619 kg at (*Ta*) 20.5 °C, 25 °C, 35 °C, 45 °C and 50 °C, respectively. This proves the relationship of the ambient temperature (*Ta*) to the amount of ice produced from the system.

Fig. 17. The variation of DIP with ambient temperature.

XIII. CONCLUSION

In this study designed a solar adsorption ice plant consisting of six refrigeration units driven by activated carbon and methanol as a working pair to produce a ton of ice daily. Each unit has a separate adsorbent bed connected with its own condenser, valve, and evaporator. A simulation

program was applied in Mecca climate, and the result was as follows:

- It could produce a ton of ice per day by 42 evacuated tube collectors in a total area of 100 m² in a climate of Makkah with an amount of 3240 kg of activated carbon and 1068 kg of methanol in the evaporator.
- The coefficient of performance (*COP*) for the system reaches 0.9 with generation temperature 79 °C and condenser and evaporator temperature are 35 °C and -5 °C, respectively.
- Increasing generation temperature contributes to the reduction *COP* where the best *COP* was at 79 °C (Td). It could pass out this problem by control of mass flow rate.
- The performance of the system is greatly affected by ambient temperature than solar radiation. Therefore, the best performance and largest amount of ice was found in the winter season.
- The amount of mass of ice is directly affected by ambient temperature.
- The condition of Makkah weather is suitable for using solar adsorption ice maker because wealthy of solar radiation long the year.

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