CSCanada
Energy Science and Technology
Vol. 3, No. 2, 2012, pp. 18-28
DOI:10.3968/j.est.1923847920120302.216

ISSN 1923-8460[PRINT]
ISSN 1923-8479[ONLINE]
www.cscanada.net
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A Statistical Approach to Optimize the Solar Adsorption Refrigeration System

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Received 2 February 2012; accepted 3 April 2012

Abstract

Solar-powered refrigeration based on adsorption cycles is simple, quiet in operation and adaptable to small medium or large systems. Application potentials include storage of vaccines for immunization against killer diseases in remote areas, preservation of foodstuff for future use and manufacture of ice. Already Solar Adsorption Refrigeration (SAR) is a technical success, but it is not commercially competitive with either the conventional vapor compression or PV refrigerators. Further developmental research is, therefore, required for improvements in existing designs either to increase system overall performances significantly or to reduce system unit cost or both. In this study a statistical approach was used to optimize of solar adsorption air conditioning or refrigeration unit using ANOVA analysis. It was found that the coefficient of performance (COP) of a SAR system does not depend sharply on the evaporator temperature without any relation of the system conditions. Instead COP depends significantly on both condenser temperature and type of couple used in the refrigeration system. In addition some factors that concern about design could have an effect on the COP. From the optimization model the maximum value of COP was found under low condenser temperature and high generator temperature. Zeolite/water couple has the maximum COP value whereas the activated carbon has the minimum value.

Key words: Solar adsorption; Refrigeration; ANOVA; SAR

Tashtoush, G. M. (2012). A Statistical Approach to Optimize the Solar Adsorption Refrigeration System. *Energy Science and Technology*, *3*(2), 18-28. Available from: URL: http://www.cscanada.net/index.php/est/article/view/10.3968/j.est.1923847920120302.216
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NOMENCLATURE

A: collector area (m^2)
C: specific heat (J/kg·K)
h: convective heat transfer coefficient (W/m^2·K)
I: total incident solar radiation on south facing inclined surface (W/m^2)
k: thermal conductivity (W/m·K)
L: Insulation thickness (m)
m: adsorbent mass (kg)
P: pressure (Pa)
Q: heat transfer rate (W)
U: thermal resistance (m^2·K/W)
T: temperature (C)
U: overall heat loss coefficient (W/m^2·K)
Δx: Adsorbent concentration (kg/m^3)

Greek symbols

ε: emissivity
η: efficiency
θ: angle of inclination
ρ: density (kg/m^3), reflectance

Subscripts

amb: ambient
con: condenser
c: collector
ev: evaporator
reg: regenerator
t: top
g: glass
s: solar
th: thermal
e: edge
b: bottom
ref: refrigeration
ad: adsorbent
o: reference
p: plate

INTRODUCTION

Adsorption has been shown to be achieved by refrigeration for a long time, while the development of solar refrigeration systems using basic solid adsorption cycle didn't emerge until the late 1970s. This interest is mainly due to the fact that such systems are environmentally friendly and that they can produce cooling by using low waste heat source (such as industrial waste energy) as driving force. Additionally, solar adsorption refrigeration systems are attractive, mostly in remote areas without grid-connected electricity, since solar radiation is freely available, and the demand of refrigeration increases particularly in the sunny regions. Some units of solar adsorption refrigerators have been commercialized using activated carbon–methanol and zeolite–water pairs. These units were technically successful, but their costs are not competitive with the conventional vapor compression system In addition to their high costs, adsorption systems have some other drawbacks, such as low specific cooling power and low coefficient of performance, due to the weak heat transfer within the adsorbers.

Determination of suitable adsorbent–adsorbate pairs for various applications was done through various studies that also quantified the cooling COP with respect to the operating temperatures[1-3]. These also pinpointed several limitations like the low heat transfer coefficient in the adsorbent bed, which has a real influence on the thermodynamic efficiency of the system.

Following that, research focused on improving heat transfer in adsorbent beds and regenerative heat transfer between beds in case of a continuous adsorption refrigeration aiming to reduce size and cost and to increase COP. Methods investigated or in the process of examination mainly concern heat recovery between beds[4], consolidated adsorbent[5-7], thermal wave (or thermal regeneration) cycles[8-10]. Heat pipes use in this field have been shown experimentally to improve heat transfer in beds[11, 12]. In the field of adsorptive systems, different types of solid-gas pairs were studied to build adapted cooling solar systems. The Zeolite-water pair is normally chosen for refrigeration and the active carbon methanol pair for ice production. The active carbon-ammonia pair is also usable for ice production. Both refrigerator type and the ice maker type systems are examples of day/night cycle adsorptive solar cooling systems. There, the system is mainly composed of a collector packed with adsorbent, a condenser and an evaporator.

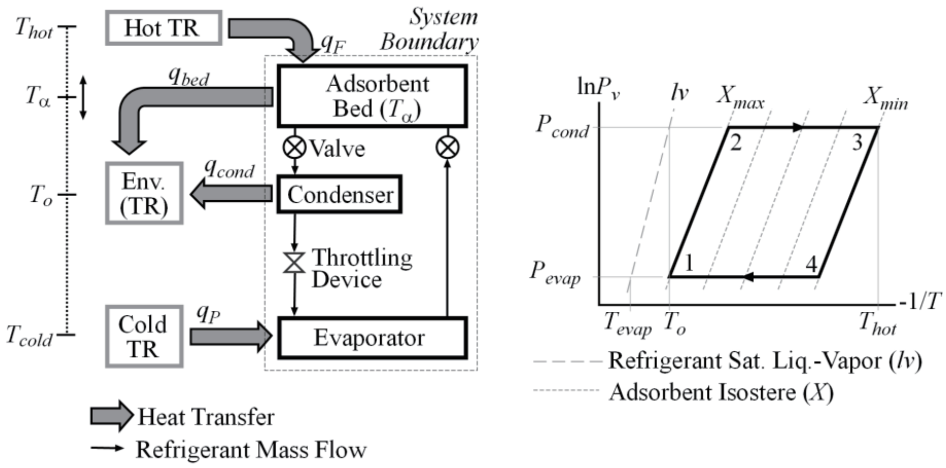
In the refrigerator type, a fluid, generally water, is frozen by the system in the water tank (located in an enclosure and expected to be kept at low temperature). The frozen fluid must be preserved at its most. As a preservative system, and by the means of a valve placed between the collector and the evaporator, heat release in the evaporator is prevented. Heat-driven sorption refrigeration cycles have existed in patent literature since at least 1909 and refrigeration were commercially available in the 1920s. In 1929, Miller described several systems, which utilized silica gel and sulfur dioxide as an adsorbent/adsorbate pair[13].

Solar adsorption heat pump and refrigeration devices are of significance to meet the needs for cooling requirements such as air-conditioning and ice making and medical or food preservation in remote areas. They are also noiseless, non-corrosive and environmentally friendly. The classical physical mathematical analysis of solar adsorption system is based on determining the COP at any instant by solving complex nonlinear set of equations. These equations are dependent upon constant factors and variables. The latter ones are the condensing, evaporating, and generating temperatures which usually called the input variables of the system. The great consumed effort for finding COP from analytical approach forced the researchers to inquire non-classical techniques to minimize the execution time for COP calculation. The value of the coefficient of performance COP is affected by three variables. These are the condensation, evaporation, and generation temperatures

Many researches had performed so much works, theoretically and experimentally, to find COP due to the change of one of these temperatures[14-17]. This project aims to build a general simple multi-dimensional mathematical models from these collected data based on using a factorial analysis and design of experiment statistical approaches. Theoretical collected data[14] were used to calculate COP under different conditions. Then the COP value for different input variables is calculated by this approach. The results are compared with classical theoretical data of COP under the same conditions. The comparison indicates very good agreement. Furthermore, data collected from experimental setup of given solar adsorption system were used as an input for the statistical procedures[18]. The predicted COP at intermediate values between the chosen points, due to the variance of one variable and keeping the other two variables constant, is compared with these values from experimental results. The comparison shows excellent agreement to predict the COP calculated by the proposed statistical procedures. This is because the statistical approach develops an optimum model that fit the given data. This optimization enables us to determine COP due to the change of one, two, and three input temperatures accurately.

1. ADSORPTION REFRIGERATION SYSTEM

Adsorption cycles are only intermittent in operation, since the adsorbent cannot move through the components, and the cycle comprises two phases: heating–desorption–condensation phase and cooling – adsorption –evaporation phase.



(a) Schematic (b) Clapeyron Diagram

Figure 1
(a) Schematic and (b) Clapeyron Diagram for an Ideal Simple Adsorption Cycle[1]

The operation of adsorption cycles for refrigeration can be easily compared to traditional compression cycles. Adsorption is a reversible process by which a fluid molecule is fixed onto a solid matrix, typically a surface or a porous material. When the molecule is fixed, it loses some energy: adsorption is exothermic. Moreover, the thermodynamic equilibrium is invariant. This invariant equilibrium can be described by the set of isosters in the Clapeyron diagram (Ln(P) vs. -1/T), as shown in Figure 1. An adsorption cycle for refrigeration, or heat pumping, does not use any mechanical energy, but only heat energy. Moreover, this type of cycle basically is a four temperature discontinuous cycle. Those four steps are:

(1) Heating
(2) Desorption
(3) Cooling
(4) Adsorption

The adsorptive cycle is intermittent. The adsorber containing the adsorbent is alternatively connected with a condenser and with an evaporator. The cycle is a succession of two periods: (a) a period of heating–desorption–condensation (1–2–3) at high pressure, (b) a period of cooling–adsorption–evaporation (3–4–1) at low pressure. High and low pressures are the saturation pressures of the adsorbate at the temperature of the condenser and the evaporator, respectively as shown in Figure 1.

2. SOLAR ADSORPTION REFRIGERATION

Solar or waste heat powered adsorption refrigeration contains only three major components (container of adsorbents, condenser and evaporator) and functions as follows. The adsorbent is packed in a hermetically sealed container painted black for solar radiation absorption. During the day, solar energy heats the high concentration of adsorbent and container to the maximum cycle temperature. At its condensing pressure corresponding to a particular temperature, the refrigerant starts desorbing from the adsorbent. As the refrigerant vapor is changed to liquid in the condenser, heat is dissipated to the surroundings. The condensations by gravity moved into a liquid receiver or directly into the evaporator. During the night cycle, the adsorbent is cooled to near ambient temperature, thus reducing the pressure of the entire system. When the adsorbent pressure equals the saturated vapor pressure of the refrigerant, the refrigerant boils in the evaporator and causes heat to be absorbed from the immediate environment. The resulting refrigerant vapor is re-adsorbed into the adsorbent, while cooling is produced.

The index of performance of a refrigerator or heat pump is expressed in terms of the coefficient of performance, COP, the ratio of desired result to input. This measure of performance may be larger than 1, and we want the COP to be as large as possible.

$$COP = \frac{\text{Desired Result}}{\text{Required Input}} \tag{1}$$

The ideal cycle for an adsorption cooling system corresponds to a hypothetical quadric-thermal machine. This device consists of two coupled machines operating at two temperature levels without mechanical energy conversion. The Carnot's COP of a quadric-thermal machine can be given by [1] as:

$$COP_{ads,rev} = \frac{1-(T_{con}/T_{reg})}{(T_o/T_{ev})-1} \tag{2}$$

Where T_{ev}, T_{con} and T_{reg} are the evaporation, condensation and regeneration temperatures, respectively. T_0 is a reference temperature, above the ambient temperature, considered to be the highest adsorption temperature possible.

For solar cooling systems, the coefficient of solar performance COP_{SAR} is usually calculated for an intermittent cycle without heat recovery, at a given regeneration temperature T_{reg} ,is:

$$COP_{SAR} = \frac{Q_{cooling}}{Q_I} = \frac{[m_1 \Delta x L(T_{ev}) - Q_1]}{m_1 \Delta x\, q_{st}(T_{reg}) + Q_2 + Q_3} \tag{3}$$

Where m_1 is the adsorbent mass, Δx the variation of adsorbate concentration, Q_1 the adsorbate heat transferred from 3 to 4 Figure (1), Q_2 the energy supplied to heat the reactor/collector from 1 to 3, Q_3 is the energy increase to heat the adsorbed mass from 1 to 3 and Q_I is the total solar energy input to the system during the day.

The collector efficiency η_c is defined as the ratio between the useful heat gains over some specified time period to the incident solar energy over the same time period Q_I; it can be expressed as:

$$\eta_c = 1 - \frac{U(T_P - T_{amb})}{\int I_P\, dt} \tag{4}$$

Where I_P is the instantaneous solar irradiation power, U the overall heat loss coefficient, T_P mean absorber plate temperature and T_{amb} is the ambient temperature. The overall heat loss coefficient U is equal to:

$$U = U_{top} + U_{edge} + U_{bottom}$$

The global heat loss coefficient at the collector top U_t was evaluated by an empirical equation given in related literature[19]. The actually coefficient of performance for such systems ranges from 0.3 to 0.8 theoretically, and ranges from 0.11 to 0.19 experimentally (as shown in the literature review) and this depends on the adsorption pair in use and on the solar collector specification.

3. STATISTICAL ANALYSIS: RESULTS AND DISCUSSION

Statistical methods are used to help us describe and understand variability. By variability, we mean that successive observations of a system or phenomenon do not produce exactly the same result. We all encounter variability in our everyday lives, and statistical thinking can give us a useful way to incorporate this variability into our decision-making processes. For example, consider our case the solar adsorption system there are a lot of factors that affect the coefficient of performance of the system like (condenser and generator temperature and type of couples). These factors represent potential sources of variability in the system. Statistics gives us a framework for describing this variability and for learning about which potential sources of variability are the most important. The most common statistical methods are:

3.1 ANOVA Analysis of Variance

The analysis of variance (ANOVA) takes place when the factors that affect the experiment have no interaction between each other so the analysis take just the main effect of each factor on the response of the process which give a primary conclusion about the most effective factor in the process but if there is an interaction between the factors of the process the factorial design take its place where the interaction is studied and more complicated analysis is needed. So in our case we will study the effect of many variables and we will apply both the ANOVA and Factorial design on our data in order to:

(1) Satisfy a primary analysis for the solar adsorption system.
(2) Determine the effects of many factors on the (COP) of the refrigeration system.
(3) Determine the possibility of interaction between these factors.

3.2 Factorial Design of Experiments

To determine the most effect of the variables like condensing, evaporating, and generating temperature on coefficient of performance (COP) for refrigeration system (SAR), factorial designs technique was used because it is widely employed in research work and because it forms the basis of other designs of considerable practical value. Factorial design determines the main effects of variable on response. The levels of the factors were selected randomly from larger populations of factor levels to insure unbiased results, and we wish to extend our conclusion to the entire population of factor levels. For example, the simplest type of factorial experiment involves only two factors, say, *A* and *B*. There are a levels of factor *A* and b levels of factor *B*. The analysis of variance can be used to hypotheses about the main factor effects of *A* and *B* and the *AB* interaction. More details of the analysis of variance and factorial design are available in many of the design of experiment and the applied statistics for engineering application text books[18].

In this study six factors were studied in many different conditions to determine their effects on the coefficient of performance of the solar refrigeration system these factors are:

(1) Temperature of generator, condenser and evaporator

(2) Couple type: Different types of couples were taken like activated carbon/methanol, zeolite/water and activated carbon/ammonia……etc.

(3) In some modifying systems the geometry of some parts of system like collector's area and the tubes radius have an effect on the COP of the system.

The data were collected from theoretical published papers that have analyzed theoretically these factors as function of the response COP. Three levels for each factors were selected randomly for example, the three levels of the couple type were (1) AC/methanol, (2) zeolite/water and (3) AC/ammonia.

Table 1
Factorial and ANOVA Output of COP vs. T_{evp} and T_{cond} and Adsorbent Type Where ($F_{0.05, 2,1} = 7.53$)

Factorial output		ANOVA output	
Source	F_{test}	Source	F_{test}
Main effect	3.03	T_{evp}	4.71
2- way interaction	0	T_{cond}	56.07
3- way interaction	0	adsorbent type	536.71

The statistical factorial and ANOVA analysis of the three factors of interest (T_{evap}, T_{cond} and the adsorbent type) was performed and the results summarized in table 1. As can be seen from the runs, the value of F_0 equal to zero for both 2-way and 3-way interaction in the factorial analysis which concludes that there is no interaction between the three factors. Based on the ANOVA analysis, the value of ($F_{0.05, 2,1} = 7.53$) was determined from the F distribution statistical table. Comparing this value with the F_{test} value of evaporator = 4.71), leads to conclude that there is no effect of evaporator temperature on the COP in contrast to both condenser temperature and type of adsorbent couple used since their values of F_{test} is extremely larger than ($F_{0.05, 2,1}$ = 7.53). Figure 2 shows the relation between the factors T_{evap}, T_{cond} and the adsorbent versus the response COP. It can be easily noted from the slope of the lines that there is no large effect of the evaporator temperature on COP compared to the other two factors. On top of that Figure 3 proves again based on the factorial analysis interaction plots that there is no interaction between the three factors under analysis.

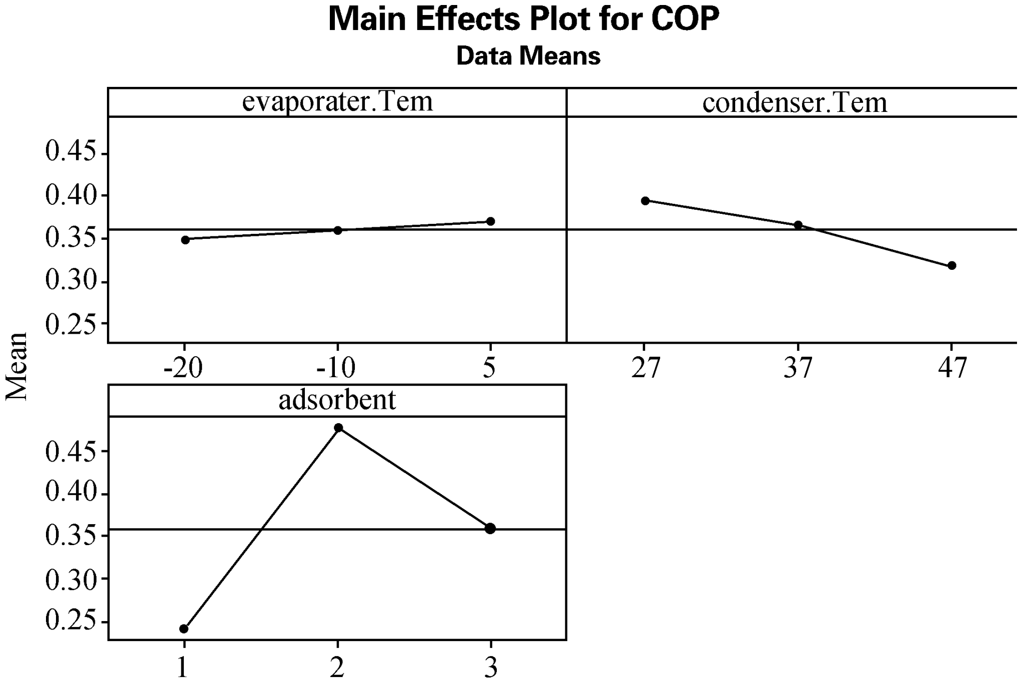


Figure 2
Main Effect Relationship for COP Vs. the Three Factors (T_{evp}, T_{cond} and Adsorbent Type)

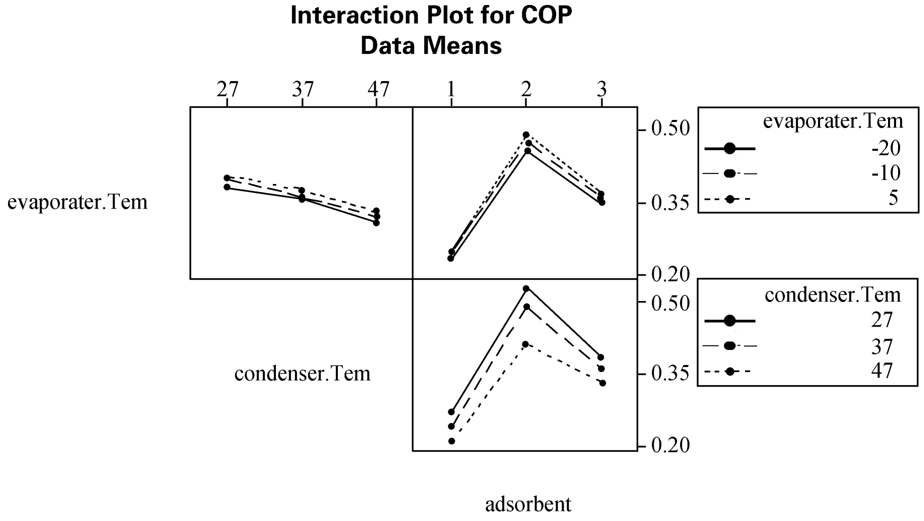


Figure 3
Interactions Drawing for the Three Factors (T_{evp}, T_{cond} and Adsorbent Type)

Table 2
Factorial and ANOVA Output of COP vs. T_{evp} and T_{gen} and Adsorbent Type Where ($F_{0.05,2,1}$ = 7.53)

Factorial output		ANOVA output	
Source	F_{test}	Source	F_{test}
Main effect	9281.43	T_{evp}	**31.38**
2- way interaction	8.2	T_{gen}	**39.50**
3- way interaction	0.12	adsorbent type	**14027.95**

Table 2 represents the statistical factorial and ANOVA analysis of the factors T_{evap}, T_{gen} and the adsorbent type. Since the value of F_{test} of the main effects is much larger than the interaction F_{test}, the interaction effect is very small compared with the main effect value. On the other hand the ANOVA analysis showed that the couple effect is very sharp then the generator temperature came second. Figure 4 proves that there is no effect of evaporator temperature on COP compared to the large effect shown for couple type and the generator temperature based on the slope of the line. Figure 5 summarize all the results discussed before for interaction plots for the factors of interest in this analysis which supports the conclusion reached before.

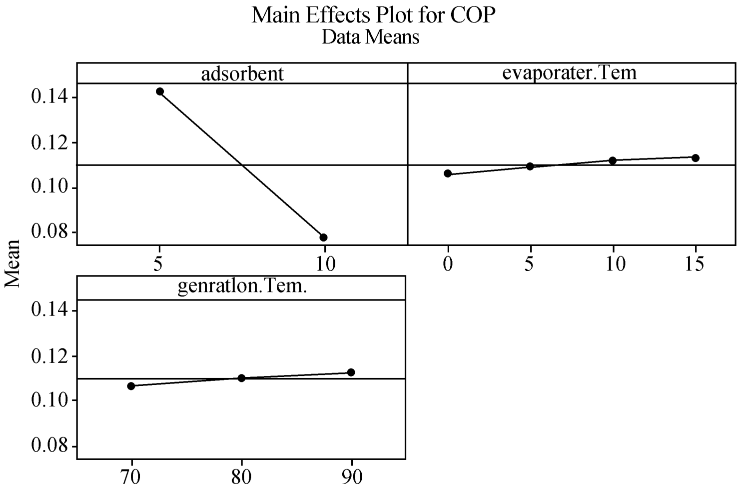


Figure 4
Main Effect Relationship for the Three Factors (Adsorbent Type, T_{evp} and T_{gen}) Vs. the COP

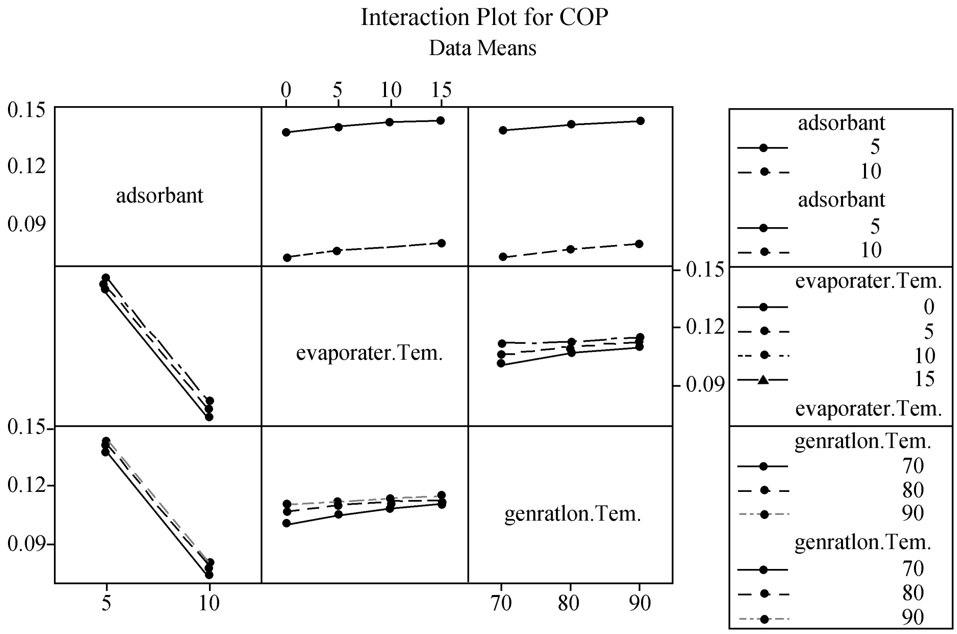


Figure 5
Interaction Drawing for Factors (Adsorbent Type, T_{evp} and T_{gen}) Vs. Cop

Table 3
ANOVA Analysis of COP vs. Radius and Collector Width Where (F_0=5.12)

ANOVA output	
Source	F_{test}
Radius	1.44
Width	7.84

Since there no interaction between the main factors of interest can be found, the factorial design has no advantage rather than ANOVA, so the analysis from now on will be limited to the ANOVA analysis only. The next step is to analyze the effect of the geometrical design factors on the COP as shown in table 3. The value of F_{test} for the two factors (radius and width) compared to the value of (F_0=5.12 from statistical F distribution table), the radius have no treatment effect on the COP whereas the width of solar collector has a large effect. Figure 6 shows the effect of the width (area) of collector is more than the effect of the tube radius which can be seen clearly from the slope of the lines, also the COP value increased with the width of solar collector and decreased with the radius of the tube.

In some modifying designs the cooling way take the indirect method by using a certain medium like water or any other liquid so some new factors appear like mass of water and the time of exposure of the day. Again the factors have no interaction conditions so no need for factorial design only ANOVA analysis was performed as shown in table 4. In this analysis, there is a sharp effect for both water mass and time of exposure since the value of F_{test} is much larger than (F_0 = 7.12 from statistical F distribution table). Figure 7 shows that the COP is increasing as water mass increased and decreasing as the time of exposure increased. The slopes of the lines prove again that the effect is very sharp as shown in the figure.

Table 4
ANOVA Analysis of COP vs. Water Mass Flow Rate and Time of Exposure Factors Where (F_0 = 7.12)

ANOVA output	
Source	F_{test}
Radius	93.44
Width	32.11

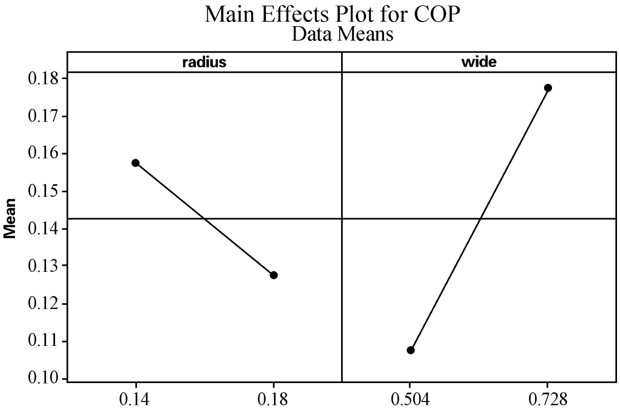


Figure 6
ANOVA Analysis of the Main Effect Drawing for the Geometry Factors

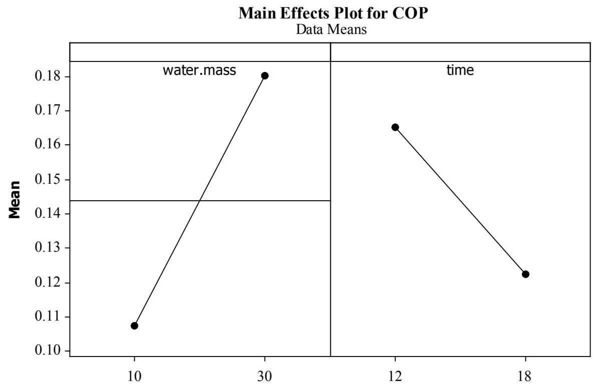


Figure 7
The Main Effect Drawing for Width and Time Factors

4. OPTIMIZATION AND SURFACE RESPONSE ANALYSIS

Table 5
Response Surface Regressions of the COP vs. T_{evp}, T_{cond} and Adsorbent

ANOVA output	
Source	F_{test}
Regresion	93.44
Linear	112.47
Square	229.52
Interaction	0.07

Table 6
Response Surface Regressions of the COP vs. T_{evp}, T_{gen} and Adsorbent

ANOVA output	
Source	F_{test}
Regresion	5971.33
Linear	15905.29
Square	6.32
Interaction	14.05

As proven before, there is no interaction between the factors so the F_{test} value in table 5 shows that the regression (ANOVA) analysis is very suitable where the value of F test is large and the most suitable regression is of a second order because it has a larger value of F test than linear model. Figure 8 shows the contours plots for the T_{evp}, T_{cond} and adsorbent factors from which the optimization analysis can be performed by locating the regions where the COP has its maximum values as shown in the response optimization diagram Figure 9. It can be seen that the maximum values of COP where found at low condenser temperature (27 ^{o}C in this case) and for the couple type (zioelt/water) with a value of 0.53 approximately. The same ANOVA and Optimization analysis was performed for the T_{evp}, T_{gen} and adsorbent factors as shown in figures 10 and 11, respectively. The maximum value of COP was found at relatively high generation temperature (above 80 ^{o}C) and for couple type of maxsorb/methanol with value of 0.145 approximately.

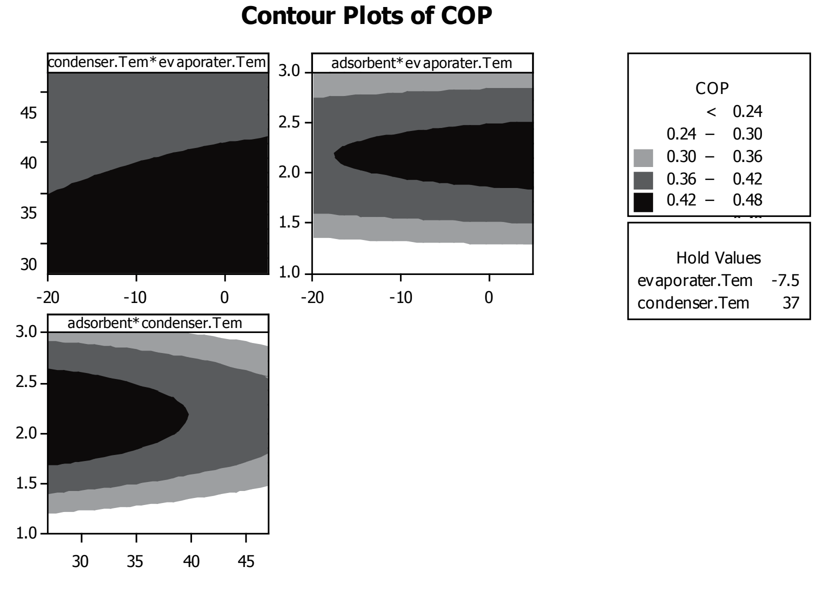


Figure 8
Contour Plots for the T_{evp}, T_{cond} and Adsorbent Factors

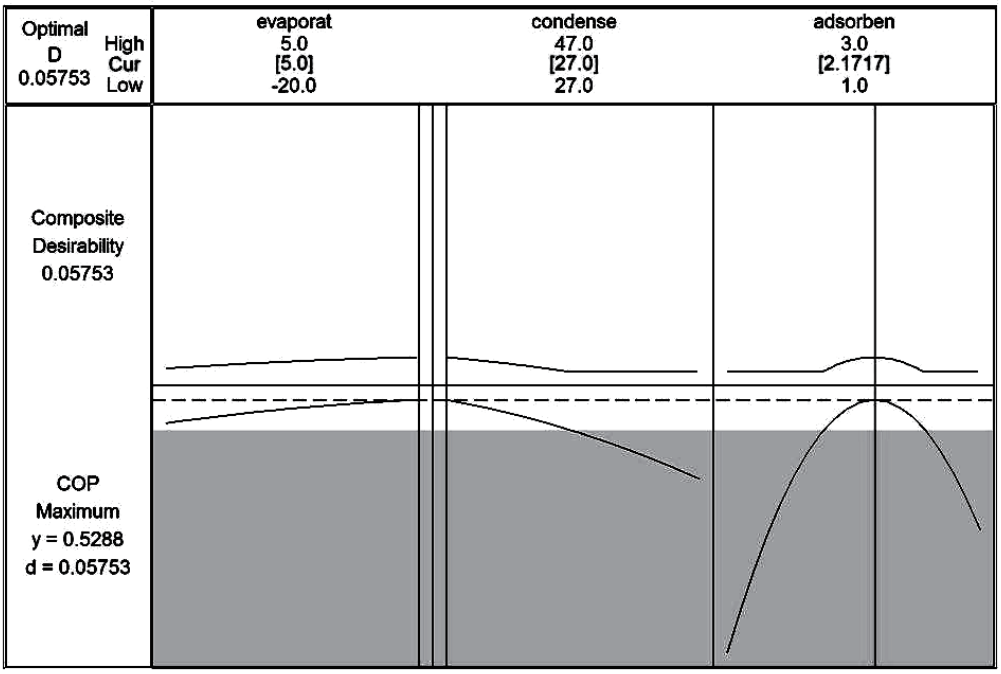


Figure 9
Optimization Plots for the T_{evp}, T_{cond} and Adsorbent Factors

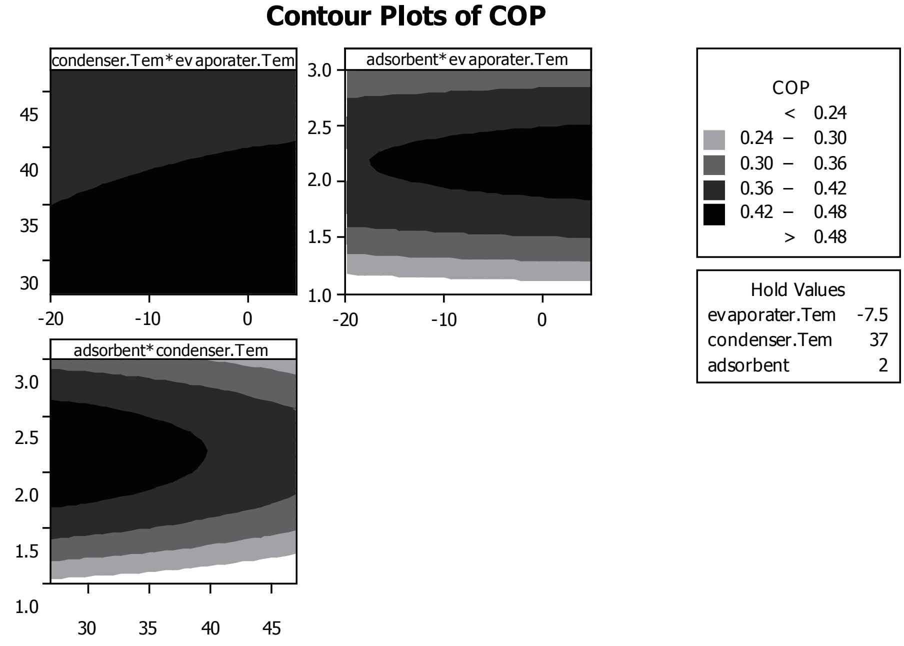


Figure 10
Contour Plots for the T_{evp}, T_{gen} and Adsorbent Factors

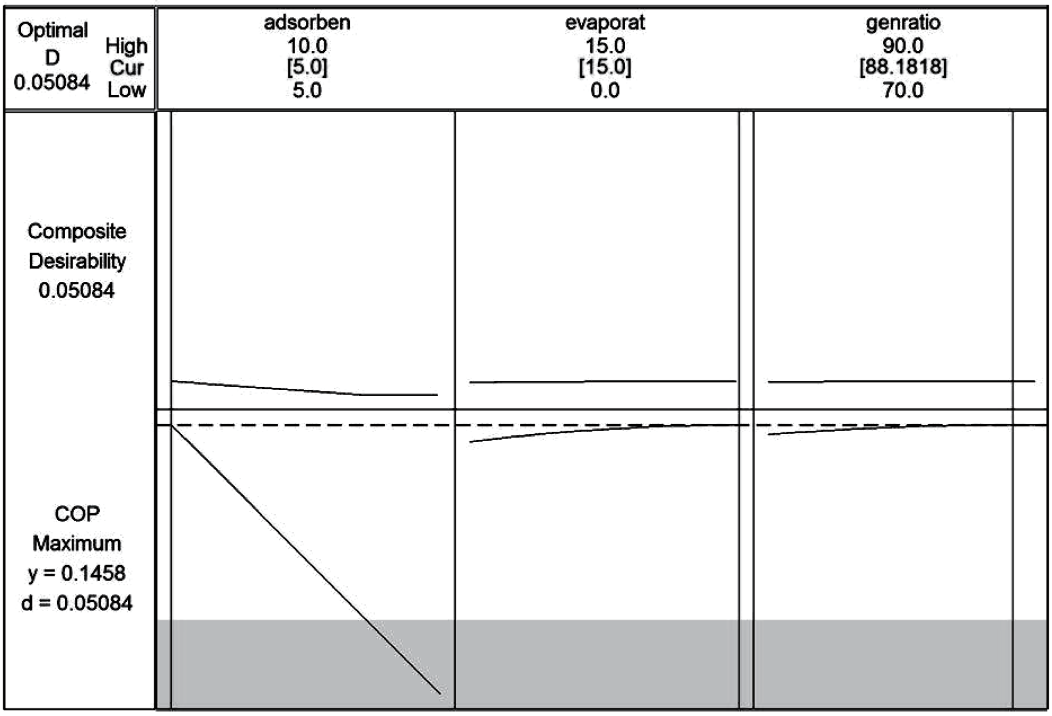


Figure 11
Optimization Plots for the T_{evp}, T_{gen} and Adsorbent

CONCLUSIONS

A statistical ANOVA approach was used to analyze and to optimize the solar adsorption refrigeration unit for general applications. It was found that the coefficient of performance of a SAR system does not depend sharply on the evaporator temperature without any relation of the system conditions. Instead COP depends significantly on condenser temperature; type of couple used in the refrigeration system and on some factors that concern about the design such as surface areas. From the optimization model the maximum value of COP where found under low condenser temperature below 27 °C and at high generator temperature above 80 °C. Zeolite/water couple has the maximum COP value where the activated carbon has the minimum value.

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