International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:13, No:4, 2019

Solar-Powered Adsorption Cooling System: A Case Study on the Climatic Conditions of Al Minya

El-Sadek H. Nour El-deen, K. Harby

***Abstract*—**Energy saving and environment friendly applications are turning out to be one of the most important topics nowadays. In this work, a simulation analysis using TRNSYS software has been carried out to study the benefit of employing a solar adsorption cooling system under the climatic conditions of Al-Minya city, Egypt. A theoretical model was carried out on a two bed adsorption cooling system employing granular activated carbon-HFC-404A as working pair. Temporal and averaged history of solar collector, adsorbent beds, evaporator and condenser has been shown. System performance in terms of daily average cooling capacity and average coefficient of performance around the year has been investigated. The results showed that maximum yearly average coefficient of performance (COP) and cooling capacity are about 0.26 and 8 kW respectively. The maximum value of the both average cooling capacity and COP cyclic is directly proportional to the maximum solar radiation. The system performance was found to be increased with the average ambient temperature. Finally, the proposed solar powered adsorption cooling systems can be used effectively under Al-Minya climatic conditions.

***Keywords*—**Adsorption, solar energy, environment, cooling, Egypt.

I. Introduction

ENERGY saving and environment friendly applications are turning out to be one of the important topics nowadays. The most popular system for refrigeration and air conditioning is employing vapor compression cooling systems due to its high COP [1]. These systems consume high-grade energy and pollute the environment due to the used harmful refrigerants. Approximately 10-20% of all the produced electricity in the world is consumed by refrigeration and air-conditioning systems. In Egypt, refrigeration and air-conditioning in the domestic sector consume about 32% of the total electricity consumed [2].

Due to the environmental impact and the global energy crisis, utilizations of thermally driven cooling systems are becoming one of the most popular topics in energy research field nowadays. Middle East region, especially Egypt enjoys the availability of a large amount of solar energy through the day time. Therefore, thermally driven adsorption chillers can be considered as one of the possible alternatives to the conventional vapor compression cooling systems in these regions in terms of energy consumption and environmental issues [3], [4]. Adsorption cooling systems can be driven by low grade heat sources such as solar energy and waste heat source.

Different theoretical and experimental investigations have been carried out on the performance analysis of adsorption cooling system powered by low grade heat sources such as solar energy and waste heat [5]-[12].

The Middle East region especially Egypt has a large abundant solar energy and long daily sunny hours. Using of a part of the available solar energy in cooling applications could be a promising option to minimize the electric power consumption.

Solar collector is an important part in solar adsorption chillers because it provides the driving energy for cooling system operation. Flat-plate collector type is usually used in solar adsorption cooling chillers [13]-[16]. Some attention has also been given to using concentrator collector types [1], [18], specifically compound parabolic concentrators type (CPCs) [19], [20]. CPCs can attain higher temperatures grades compared to flat-plate collectors, and therefore the system can used to produce ice even on overcast days.

Louajari et al. [21] investigated the performance of an adsorption system in a solar flat plate collector with and without fins. They show that the fins in the solar collector system increase the COP of the system. The results showed that due to the use tube with fins, the system COP raises from 0.075 to 0.11. Balghouthi et al. [22] modelled 11 kW solar adsorption cooling system with 30 m^2 flat plat solar collector and 800 L water storage tank. The results showed that the system was suitable for Tunisian weather conditions. Alam et al. [23] analytically investigated the performance of silica gel/water adsorption chiller based on the weather condition of Tokyo, Japan. It was found that 15 parabolic solar collectors (each of 2.415 m^2) are required to attain 85 °C to operate the system. Results showed the possibility of achieving a solar COP of around 0.3 and a system COP of about 0.55. Li et al. [24] experimentally investigated a solar powered adsorption cycle for ice making using methanol on activated carbon pair. Two flat plate collectors have been attached to the bed, with 1.5 m^2 total surface area. Results showed that the ice production could exceed 4.5 kg with 16 MJ of radiation and 0.75 m^2 collector.

A simulation study was carried out by El-Sharkawy et al. [25] on the performance of a solar powered adsorption cooling system. The system performance was investigated at actual solar weather conditions of Cairo and Aswan in Egypt and the coastal city of Jeddah in Saudi Arabia. They found that solar driven adsorption chiller has promising potential applications in the Middle East region. The maximum cooling capacity under Cairo and Jeddah climate conditions was about 14.8 kW

*El-Sadek H. Nour El-deen , K. Harby are with the Department of Mechanical Power Engineering and Energy, Faculty of Engineering, Minia University, Minia 61517, Egypt (*Corresponding author: phone: +201114753726, e-mail: dr_elsadekhn2000@mu.edu.eg).

whilst for system working under weather conditions of Aswan, it is about 15.8 kW. The potential application of using solar driven adsorption cooling systems in Jordan has been investigated by [8]. The payback period of the proposed solar system is also carried out by using an economic analysis.

As shown from the literature survey, there is no study for the effect of weather condition of Al-Minya city at Egypt on performance of adsorption cooling system. In addition, performance of adsorption refrigeration systems employing granular activated carbon-HFC-404A as a working pair has not been investigated yet. In this work a simulation analysis using TRNSYS software has been performed on the performance of two-bed adsorption cooling system powered by solar energy. The climatic conditions and metrological data of Al-Minya city (28.0871° N, 30.7618° E) at Egypt were used. Year round performance tests of this solar system are performed.

II. System Description and Operation Procedure

The whole system consists mainly of two cycles as shown in Fig. 1. The first cycle is the solar cycle, when the solar heating energy is collected by the evacuated tube collector during daylight hours. Tank (I) and Tank (II) have a volume of 0.5 and 1.5 m^3 respectively. The hot water is circulated between tank (I) and tank (II) by pump I and pump II respectively (0.7 kgs^{-1} water flow rate) to maintain homogenous hot water temperature to the adsorption system. In the adsorption cycle, pump (III) is used to deliver hot water (0.6 kgs^{-1} water flow rate) from Tank (II) to the system when cooling demand is required at specific operating hours. The operation procedure of the two-bed adsorption cooling system can be found in the literature [26]-[28].

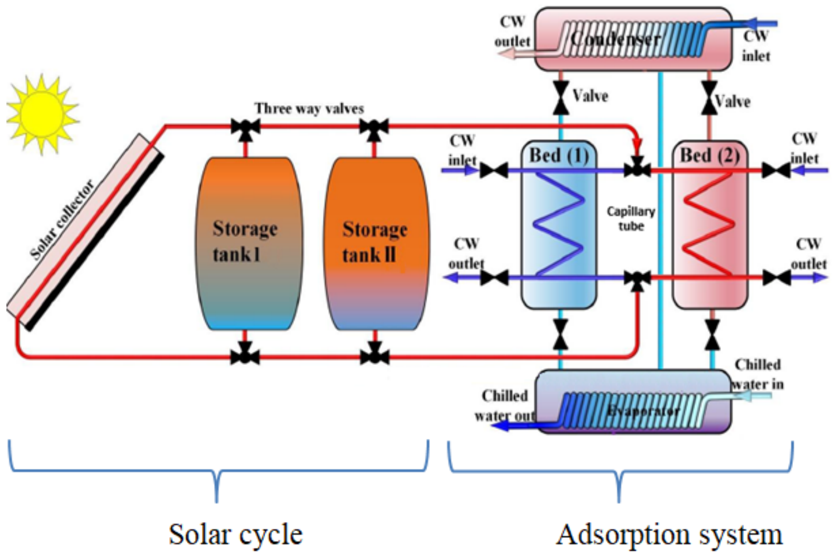

Fig. 1 Schematic diagram of the proposed two beds adsorption chiller

A TRNSYS project has been built as shown in the TRNSYS screen capture of Fig. 2. The system consists mainly of evacuated tube solar collector, two storage water tanks A and B, adsorption chiller, three ware pumps and thermostat. Metrological weather data of Al-Minya (28.0871° N, 30.7618 °E) have been used as a feeding data to drive the evacuated solar collector of 6 m^2 surface area. A climatic weather data files from TRNSYS 16 [29] for Al-Minya city at Egypt is used. The adsorption cycle model is written in TRNSYS software readable MATLAB code.

The tilt angle of the collector surface is considered as the latitude angle of Al-Minya city as it was considered as the optimum tilt angle for the collectors.

III. Mathematical Model

Adsorption uptake of granular activated carbon-HFC-404A pair is calculated by Dubinian-Astakhov (D-A) as shown by (1) [30]. Adsorption rate can be shown by the linear driving force (LDF) model of (2).

$$C = C_o exp\left(-\left(\frac{RT}{E} ln\left(\frac{P_s}{P}\right)\right)^n\right) \quad (1)$$

$$\frac{\partial C}{\partial t} = \frac{FD_s}{{R_p}^2}(C_0 - c) \quad (2)$$

Table I illustrates the main parameters used in the model [30].

TABLE I
Simulation Parameters of Granular Activated Carbon-HFC-404A Adsorption Pair

Parameter	value	Units
C_0,	1.035	cm^3/g
E,	98.14	kJ/kg
n	1.03	-
H_{st}	38363.347	kJ/kg

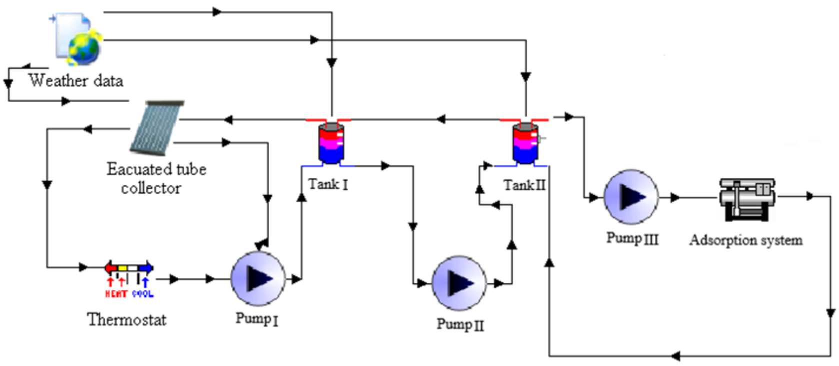

Fig. 2 A print screen for solar assisted adsorption system using TRNSYS software

Isosteric heat of adsorption can be given by:

$$H_{st} = h_{fg} + E\left[ln\left(\frac{C_0}{C}\right)^{\frac{1}{n}}\right] + \frac{ET\alpha}{n}\left[ln\left(\frac{Co}{C}\right)\right]^{\frac{1-n}{n}} \quad (3)$$

The energy balance equation for the adsorption bed is given by [31]:

$$\left[\left(m_{ac}c_{p_{ac}} + m_{ac}c_{p_{ref}}C\right) + \left(m_{hex}c_{p_{hex}}\right)\right]\frac{dT_{bed}}{dt} = m_{ac}H_{st}\frac{dC_{bed}}{dt} - m_w^{\cdot}c_{p_w}\left(T_{w,out} - T_{w,in}\right) \quad (4)$$

For a small temperature difference across heating/cooling fluid, the outlet can be given by the log mean temperature difference (LMTD) method:

$$T_{w,out} = T_{bed} + \left(T_{w,in} - T_{bed}\right)exp\left[\frac{-(UA)_{bed}}{(m^{\cdot}c_p)_w}\right] \quad (5)$$

The energy balance across the condenser can be expressed as:

$$\frac{dT_c}{dt} = m_{ac}h_{fg}\frac{dC_{des}}{dt} + m_{ac}c_{p_{ac}}\left(T_{des} - T_{sur}\right)\frac{dC_{des}}{dt} - U_c\left(T_c - T_{sur}\right)A_{hex} \quad (6)$$

The energy balance equation of the evaporator can be given as,

$$\left(m_{ref}c_{p_{ref}} + m_{hex}c_{p_{hex}}\right)_{eva}\frac{dT_{eva}}{dt} = -m_{ac}h_{fg}\frac{dC_{ads}}{dt} - m_{chill}^{\cdot}c_{p_{chill}}\left(T_{chill,out} - T_{chill,in}\right) \quad (7)$$

Adsorption cooling system performance is commonly given by the cooling capacity and the COP.

$$Q_{cap} = \int_0^t (m^{\cdot}cp_w)_{chill}\left(T_{chill,out} - T_{chill,in}\right)\frac{dt}{t_{ads}} \quad (8)$$

$$\text{COP} = \frac{\int_0^t (m^{\cdot}cp_w)_{chill}(T_{chill,out}-T_{chill,in})dt}{\int_0^t (m^{\cdot}cp_w)_{des}(T_{hw,in}-T_{hw,out})dt} \quad (9)$$

$$\text{COP}_{solar} = \frac{\int_0^t (m^{\cdot}cp_w)_{chill}(T_{chill,out}-T_{chill,in})dt}{\int_0^t \eta \breve{a} A_{sc} I dt} \quad (10)$$

The values of the physical parameters of the system components that are used in the calculations are shown in Table II.

TABLE II
PHYSICAL PARAMETERS OF ADSORPTION COOLING SYSTEM

Parameter	value	Units
m·cw	0.5	kg/s
cpw,	4.18	kJ/kg.K
cpac,	1.4	kJ/kg.K
mac,	95	kg
(UA)bed,	2500	W/K
(UA)con,	15000	W/K
(UA)eva,	5000	W/K

IV. Result and Discussion

In this section, the climatic data of Al-Minia city have been presented firstly and then the simulation results of the effect of the weather conditions on the proposed solar assisted adsorption chiller are shown.

A. Climate Data

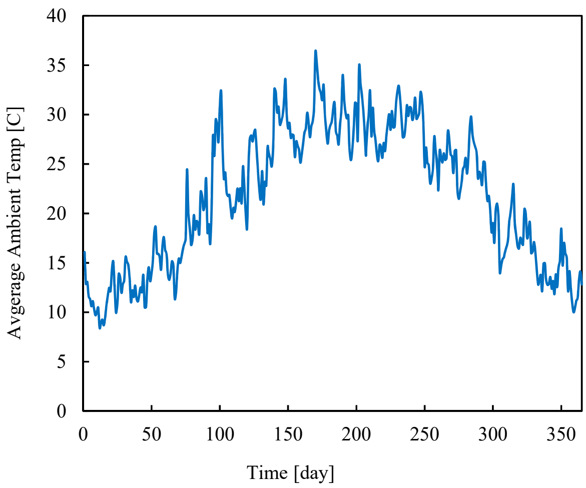

Fig. 3 Average daily variation of ambient temperature for Al-Minya city

The average daily variation of ambient temperature and solar radiation for one year of Al-Minya city are shown in Figs. 3 and 4 respectively. As can be shown, the highest average ambient temperature was in August month with average ambient temperatures of about 30°C and about 1200 Wm^{-2} average daily solar radiation.

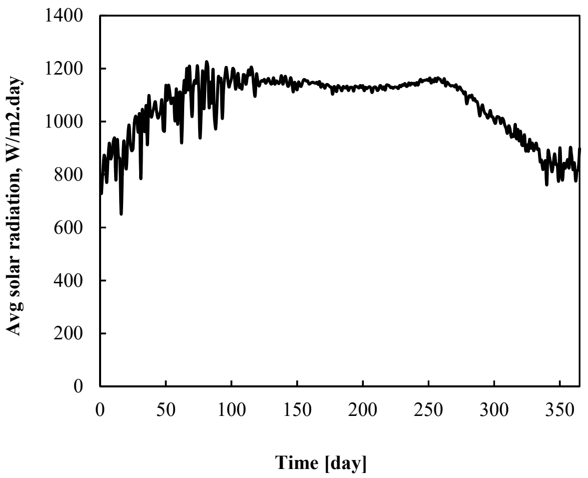

Fig. 4 Average daily variation of solar radiation for Al Miya city

As shown previously, August is the hottest month of the year for the Al-Minya city and day of 15 August has been also chosen as a clear day. Therefore the weather conditions of this day will be used in the performance investigation of the proposed adsorption system.

Figs. 5 and 6 show hourly presentation of ambient temperature and solar radiation respectively in 15 August. As shown, at night time, the radiation and surrounding temperature are zero and increasing gradually throughout the day.

Fig. 7 shows the variation of the inlet hot water temperature to the proposed adsorption chiller from the collector during August. As shown, the greatest hot water temperature is around 93°C that is controlled by the temperature regulator.

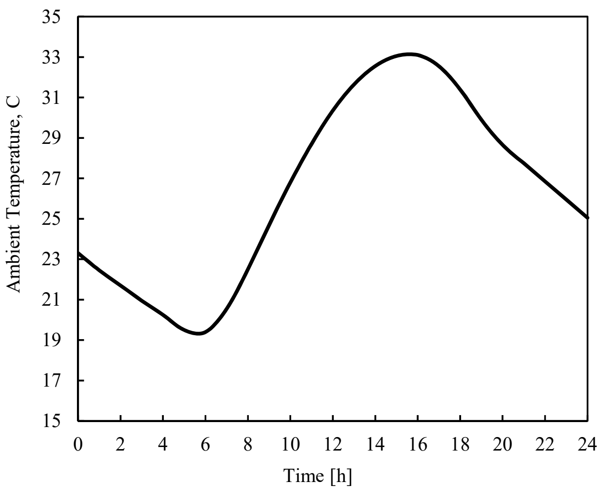

Fig. 5 Hourly presentation of ambient temperature profile in 15 August

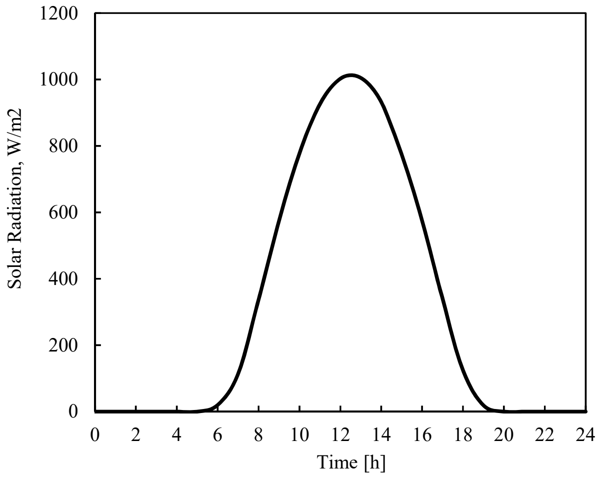

Fig. 6 Hourly presentation of solar radiation profile in 15 August

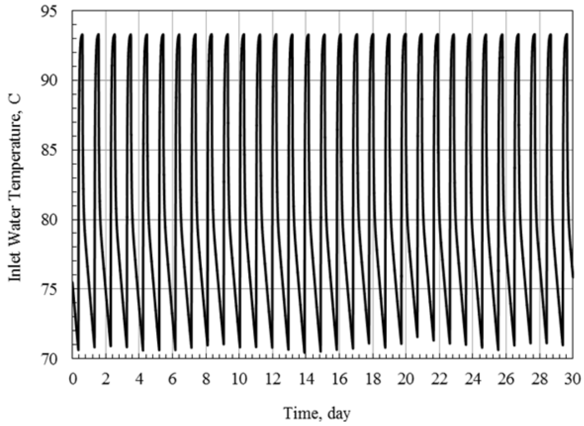

Fig. 7 Variation of hot water inlet temperature for August

B. Performance Analysis of the proposed Solar Cooling System

The developed mathematical model of differential equations (1)-(10) which have been described in Section III is coded into MATLAB and solved simultaneously by numerical integration ODE 45. The MATLAB has been run by TRNSYS 16 [29]. The meteorological data of Al-Minya city, Egypt have been selected as weather feeding data for the simulation. The simulation cycle was performed for a cycle time of 900 s and switching time of 50 s.

Fig. 8 presents the temperature profiles of the inlet hot water from the solar collector (T_{wi}), the adsorption/desorption beds (T_{bed1}/T_{bed2}), and average chilled water temperature (T_{eva}) based on the climate data of Al- Minia city in 15 August for a time interval between 12:00 and 13:00. It is seen that, the inlet water temperature (Twi) from the solar collector is almost constant at 77 ^{o}C due to the used double storage tanks. The temperature of adsorber/desorber beds varies from 30 to 73 ^{o}C whilst the average chilled water fluctuating around 12 ^{o}C.

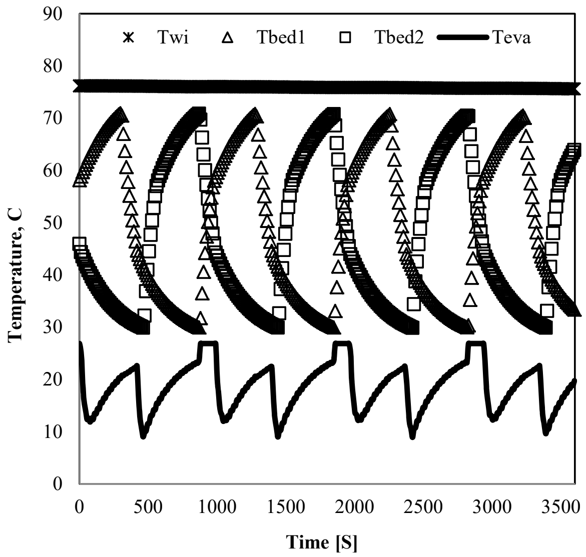

Fig. 8 Temperature profile of the adsorption cooling system for one hour

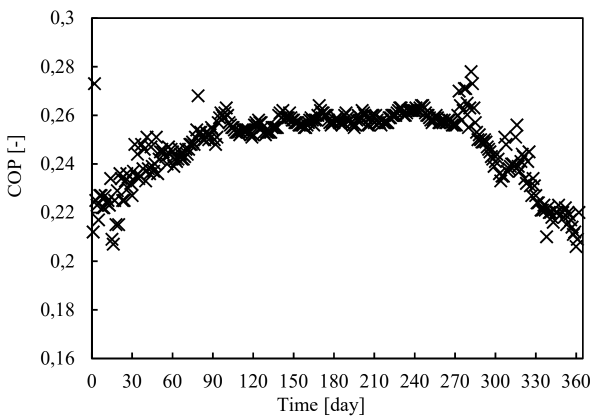

Fig. 9 Average daily COP of the proposed solar driven adsorption chiller during the year

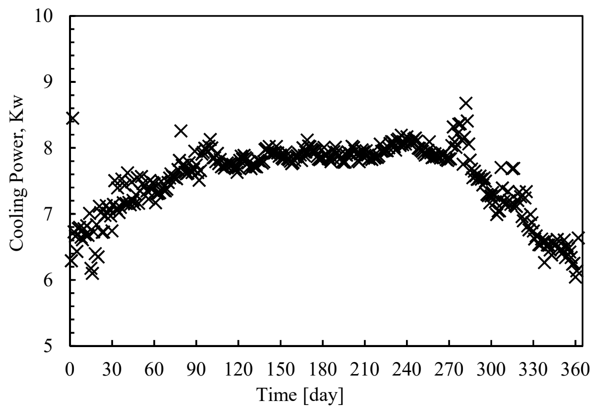

Fig. 10 Average daily cooling capacity of the proposed solar driven adsorption chiller during the year

Figs. 9 and 10 show the average daily COP and cooling capacity around 360 day of proposed solar-driven adsorption system. As shown from the figure, the average cycle COP and cooling capacity increase until they reach the maximum value of about 0.26 at the month of August. This is due to the effect of high temperatures and solar intensity in this month as illustrated previously in details.

The maximum values of COP and cooling capacity of the proposed system increase with the increase of inlet water temperature and ambient temperature and decrease with the decrease of the average solar radiation.

The maximum value of the both average cooling capacity and COP cyclic is directly proportional to the maximum solar radiation; this is also concluded by El-Sharkawy et al. [25]. The maximum average yearly cooling capacity that can be achieved from the proposer system is attained during August is about 8 kW.

V. Conclusion

In this study, effect of weather conditions of Al-Minya city on the performance of a proposed solar powered adsorption cooling system is carried out. It has been found that there is a reasonable agreement between the growth of the cooling effect and the increase of the ambient temperature. The highest value of the performance of system (COP) and cooling effect increases with the increase of hot water inlet temperature and surrounding temperature and decreases with the decrease of the average solar radiation. The maximum yearly average COP and cooling capacity are about 0.26 and 8 kW respectively. No significant effect was found for the latitude of Al-Minya on the average daily COP and specific cooling power. The proposed solar powered adsorption cooling systems can be used effectively under Al-Minya climatic conditions.

References

[1] K. Harby, Doaa R. Gebaly, Nader S. Koura, “Mohamed S. Hassan, Performance improvement of vapor compression cooling systems using evaporative condenser: An overview“, Renewable and Sustainable Energy Reviews, vol. 58, pp. 347-360, 2016.

[2] International Energy Agency (IEA). “Key energy statistics“. 1st ed. Paris: OECD/IEA; 2010.

[3] S. Ehab, K. Harby, A. Askalany, M. Diab, A. Alsaman, “Weather effect on a solar powered hybrid adsorption desalination-cooling system: A Case Study of Egypt’s Climate“, Applied Thermal Engineering, vol. 124, pp. 663-672, 2017.

[4] H, Hassan, A. Mohamad, “A review on solar-powered closed physisorption cooling systems“, Renewable Sustainable Energy Rev., vol. 16, pp. 2516-38, 2012.

[5] M. Clausse, K. Alam, F, Meunier, “Residential air conditioning and heating by means of enhanced solar collectors coupled to an adsorption system“, Sol Energy, vol. 82, pp. 885-92, 2008.

[6] S. Vasta, G. Maggio, G. Santori, A. Freni, F. Polonara, G. Restuccia, “An adsorptive solar ice-maker dynamic simulation for north Mediterranean climate“, Energy Convers Manage, vol. 49, pp. 3025-35, 2008.

[7] K. Alam, B. Saha, A. Akisawa, “Adsorption cooling driven by solar collector: a case study for Tokyo solar data“, Appl Therm Eng, vol. 50, pp. 1603-1609, 2013.

[8] A. Fasfous, J. Asfar, A. Al-Salaymeh, A. Sakhrieh, Z. Al_hamamre, A. Al-bawwab, “Potential of utilizing solar cooling in The University of Jordan“, Energy Convers Manage, vol. 65, pp. 729-35, 2013.

[9] W Wang, Q. TF, R. Wang, “Influence of degree of mass recovery and

heat regeneration on adsorption refrigeration cycles", Energy Convers Manage, vol. 43, pp. 733-41, 2002.
[10] M. Verde, K. Harby, J. M. Corberán, "Optimization of thermal design and geometrical parameters of a flat tube-fin adsorbent bed for automobile air-conditioning", Applied Thermal Engineering, vol. 111, pp. 489-502, 2017.
[11] M. Verde, K. Harby, R. Boer, J. M. Corberán, "Performance evaluation of a waste-heat driven adsorption system for automotive air-conditioning: Part I- Modeling and experimental validation", Energy, vol. 116, pp. 526-538, 2016.
[12] M. Verde, K. Harby, R. Boer, J. M. Corberán, "Performance evaluation of a waste-heat driven adsorption system for automotive air-conditioning: Part II- Performance optimization under different real driving conditions", Energy, vol. 115, pp. 996-1009, 2016.
[13] E. Anyanwu, C. Ezekwe, "Design, construction and test run of a solid adsorption solar refrigerator using activated carbon/methanol, as adsorbent/adsorbate pair", Energy Convers, Manag, vol. 44, pp. 2879-2892, 2003.
[14] Y. Fan, L. Luo, B. Souyri, Review of solar sorption refrigeration technologies: Development and applications". Renew. Sustain. Energy Rev, vol. 11, pp. 1758-1775, 2007.
[15] F. Lemmini, A. Errougani, "Building and experimentation of a solar powered adsorption refrigerator". Renew. Energy, vol. 30, pp. 1989-2003, 2005.
[16] M. Louajari, A. Mimet, A. Ouammi, "Study of the effect of finned tube adsorber on the performance of solar driven adsorption cooling machine using activated carbon–ammonia pair". Appl. Energy, vol. 88, pp. 690-698, 2011.
[17] A. Fadar, A. Mimet, M. Pérez-García, "Modelling and performance study of a continuous adsorption refrigeration system driven by parabolic trough solar collector". Sol. Energy, vol. 83, pp. 850-861, 2009.
[18] C. Li, R. Wang, L. Wang, X. Li, Y. Chen, "Experimental study on an adsorption icemaker driven by parabolic trough solar collector". Renew. Energy, vol. 57, pp. 223-233, 2013.
[19] M. González, L. Rodríguez, "Solar powered adsorption refrigerator with CPC collection system: Collector design and experimental test". Energy Convers. Manag. vol. 48, pp. 2587-2594, 2007.
[20] O. Headley, A. Kothdiwala, I. McDoom, "Charcoal-methanol adsorption refrigerator powered by a compound parabolic concentrating solar collector". Sol. Energy, vol. 53, pp. 191-197, 1994.
[21] M. Louajari, M. Abdelaziz imet, O. Ahmed, "Study of the effect of finned tube adsorber on the performance of solar driven adsorption cooling machine using activated carbon-ammonia pair", Applied Energy, vol. 88, pp. 690-698, 2011.
[22] M. Balghouthi, M. Chahbani, A. Guizani, "Feasibility of solar adsorption air conditioning in Tunisia", Build Environ, vol. 43, pp. 1459-70, 2008.
[23] K. Alam, B. Saha, A. Akisawa, "Adsorption cooling driven by solar collector: a case study for Tokyo solar data", Appl Therm Eng, vol. 50, pp. 1603-1609, 2013.
[24] M. Li, R. Wang, Y. Xu, J. Wu, and A. Dieng, "Experimental study on dynamic performance analysis of a flat-plate solar solid-adsorption refrigeration for ice maker", Renewable Energy, vol. 27, pp. 211-21, 2002.
[25] I. El-Sharkawy, H. Abdel-Meguid, B. Saha, "Potential application of solar powered adsorption cooling systems in the Middle East", Appl Energy, vol. 126, pp. 235-45, 2014.
[26] C. Y. Tso, Y .H. Christopher, S. C. Fu, "Performance analysis of a waste heat driven activated carbon based composite adsorbent-Water adsorption chiller using simulation model", International Journal of Heat and Mass Transfer, vol. 55, pp. 7596-7610, 2012.
[27] B. B. Saha, I. I. El-Sharkawy, A. Chakraborty, S. Koyama, "Study on an activated carbon fiber-ethanol adsorption chiller: Part I- system description and modelling", Int J Refrig, vol. 30, pp. 86-95, 2007.
[28] B. B. Saha, I. I. El-Sharkawy, A. Chakraborty, S. Koyama, "Study on an activated carbon fiber-ethanol adsorption chiller: Part II - performance evaluation", Int J Refrig, vol. 30, pp. 96-102, 2007.
[29] TRNSYS 16.0, "Mathematical Reference by the Solar Energy Laboratory", University of Wisconsin-Madison, Vol. l5, 2006.
[30] M. Ghazy, A. Ahmed, K. Harby, M Ahmed, Adsorption isotherms and kinetics of HFC-404A onto bituminous based granular activated carbon for storage and cooling applications, Applied Thermal Engineering, Vol. 105, pp. 639-645, 2016.
[31] K. Habib, B. B. Saha, A. Chakraborty, S. Koyama, "Srinivasan K. Performance evaluation of combined adsorption refrigeration cycles", Int J Refrig, vol. 34, pp.129-37, 2011.