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Potential application of solar powered adsorption cooling systems in the Middle East

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HIGHLIGHTS

- Theoretical investigation of adsorption chiller driven by solar CPC is presented.
- The study is performed using the climate conditions of the Middle East region.
- Two system configurations (with/without hot water buffer storage) are proposed.
- Temporal history of solar CPC, sorption reactors, evaporator and condenser are predicted.
- Cyclic and average daily cooling capacity, cycle COP and solar COP are studied.

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ABSTRACT

This paper presents a theoretical investigation on the performance of solar powered silica gel/water based adsorption cooling system working under climate conditions of the Middle East region. Actual solar data of Cairo and Aswan located, respectively, in the north and south of Egypt and the coastal city Jeddah on the Red Sea in Saudi Arabia are used in this study. Dynamic behavior of adsorption chillers driven by compound parabolic solar collector is presented. Two system configurations have been considered herein; (i) adsorption chiller is directly connected to the solar collectors, (ii) hot water buffer storage is installed between adsorption chiller and solar collectors. Temporal history of solar collector, sorption reactors, evaporator and condenser has been predicted. System performance in terms of cooling capacity, daily average cooling capacity, cycle COP and solar COP has been estimated. Results show that the maximum cyclic cooling capacity of the system working under Cairo and Jeddah climate conditions reaches about 14.8 kW and about 15.8 kW for Aswan climate conditions.

1. Introduction

Energy demand, global warming and ozone depletion are serious problems that call for immediate solutions. Among energy forms, electricity is the main constitute of modern daily life activities. According to International Energy Agency (IEA); fossil fuels present about two-third of the fuel shares of electricity generation in 2010 [1]. Approximately 15% of electricity generated in the whole world is utilized for refrigeration and air-conditioning processes according to the estimation of the International Institute of Refrigeration in Paris. Moreover, the energy consumption for air-conditioning systems was estimated to be 45% of the whole households and commercial buildings [2]. For Middle East region, particularly in Egypt, the domestic sector air-conditioning devices consume about 32% of the electrical energy whilst for commercial building in Saudi Arabia, air-conditioning devices consume from 38% to 60% of the electricity [2,3]. However, the Middle East region has abundant solar energy and long daily sunny hours. Utilizing of a part of the available solar energy in air-conditioning applications could be a promising option to reduce the electricity consumption. Absorption, adsorption and desiccant cooling are the most common technologies available in solar refrigeration and air-conditioning applications. Solar powered adsorption cooling systems, in particular, have the advantages of using clean energy and environmental friendly refrigerants. Moreover, they can be driven by low

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Nomenclature

A_n	coefficient in Eq. (7)
a_0, a_1	coefficients in Eq. (4)
B_n	coefficient in Eq. (8)
b_1	coefficient in Eq. (4)
CC	cyclic average cooling capacity (kW)
COP_{cycle}	average cycle coefficient of performance (−)
COP_{solar}	average solar coefficient of performance (−)
C_P	specific heat capacity (kJ kg^{-1} K^{-1})
D_s	surface diffusivity (m^2 s^{-1})
D_{so}	pre-exponential constant (m^2 s^{-1})
E_a	activation energy (J mol^{-1})
I	solar radiation (W m^{-2})
K_0, K_1, K_2	coefficients in Eq. (2)
M	mass (kg)
$\dot{m}$	mass flow rate (kg s^{-1})
P	equilibrium pressure (kPa)
P_s	saturation pressure (kPa)
Q_{st}	isosteric heat of adsorption (kJ kg^{-1})
R_u	universal gas constant (kJ kmol^{-1} K^{-1})
R_p	radius of adsorbent particle (m)
T	temperature (K)
t	time (s)
W	adsorption equilibrium uptake (kg kg^{-1})
w	instantaneous adsorption uptake (kg kg^{-1})
w	coefficient in Eq. (4)
U	overall heat transfer coefficient (W m^{-2}K^{-1})
A	heat transfer area (m^2)
η	efficiency

Subscripts

ads	adsorbent/adsorption
amb	ambient
bed	adsorber/desorber bed
buff	buffer storage
c	condenser cooling water
chill	chilled water
cond	condenser
cw	cooling water
des	desorption
evap	evaporator
hw	hot water
i	component
in	inlet condition
max	maximum
min	minimum
out	outlet condition
ref	refrigerant
sc	solar collector

temperature heat source, typically below 100 °C, which can be reduced to 50 °C if multi-stage scheme is performed [4,5].

Silica gel, zeolite and carbon based materials are commonly used as adsorbents whilst water, methanol and ethanol are found to be suitable refrigerant candidates working effectively with these adsorbents [6–12]. Extensive research efforts have been conducted to improve the system performance and to reduce its footprint. A sizable number of researchers investigated, experimentally and theoretically, the performance of two-bed adsorption cooling systems [4,13–15]. Saha et al. [5] investigated the performance of a silica gel/water based dual-mode, multi-stage, multi-bed regenerative adsorption system. This system can be driven by low-temperature solar or waste heat sources of temperature between 40 and 95 °C along with a coolant at 30 °C. Heat and mass recovery schemes and reheat technique were also used to improve the system performance [16–19]. Clausse et al. [20] investigated the possibility of using solar adsorption air-conditioning during summer and direct heating during winter using enhanced compound parabolic solar collectors. The authors used activated carbon as an adsorbent and methanol as a refrigerant. Performance of the system has been investigated on the climate conditions of Orly, France. Results of this study show the possibility to keep the indoor temperature below 23 °C during summer. Moreover, using of solar collectors around the year for air-conditioning and direct heating make the solar collector installation is economically attractive. Alam et al. [21] investigated theoretically the performance of two-bed silica gel/water based adsorption cooling system driven by compound parabolic solar collectors. The authors used solar data of Tokyo, Japan. Theoretical results show that, the possibility of achieving a cycle COP of about 0.55 and a solar COP of around 0.3. A solar powered adsorption cooling system with and without heat storage was designed and experimentally tested [22]. Results show that, the system with heat storage has more stable operation compared to the system without heat storage. However, the system without heat storage was capable of obtaining similar cooling effect under same operating conditions. A solar powered silica gel/water based adsorption cooling system was constructed in the green building of Shanghai Institute of Building Science [23]. The system performance was investigated theoretically and experimentally. It was found that, under typical summer weather conditions, the average cooling capacity of the solar adsorption cooling system was 15.3 kW with the maximum value exceeding 20 kW. It was also reported that, the daily average system COP was 0.35. Effects of the variable heat source on the performance of the silica gel/water based adsorption chiller was investigated experimentally [24]. The possibility of using solar powered adsorption systems in Jordan was theoretically studied [25]. An economic analysis was also conducted in this study to estimate the payback period of the solar cooling system. A detailed overview on the developments in adsorption refrigeration systems can be found elsewhere [26].

In order to evaluate the potential use of solar cooling in the Middle East region, the performance of two-bed silica gel/water based adsorption chiller powered by solar energy is theoretically investigated. The selected cities for the present study are Cairo (30.06° N, 31.23° E) and Aswan (24.07° N, 32.92° E) located in Egypt, and the coastal city Jeddah (21.50° N, 41.94° E) on the Red Sea shore in Saudi Arabia. The climate data during summer months May, June and July are used to perform the present study.

As per our knowledge, there is a limited number of studies deal with the performance of adsorption cooling systems for application in the Middle East region. The novelties of this work are: (i) investigation of the instantaneous and daily average performance of solar powered silica gel/water based adsorption cooling system working under the actual climate conditions of the Middle East, (ii) study of the system performance for a clear day and also for severely fluctuated solar radiation conditions, and (iii) evaluation of the system performance with and without buffer and highlight the advantages and disadvantages of each configuration. It is also worthy to mention that the present simulation can capture the dynamic behavior of adsorption cooling systems including temporal and pressure histories of all heat exchangers, instantaneous and daily average cooling capacity and COP. Results derived from this study would provide useful information to the researchers who