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Design optimization of a residential scale solar driven adsorption cooling system in upper Egypt based

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A B S T R A C T

This study provides a decision support approach for selecting the best size of the main components of a small scale solar assisted, silica gel-water, adsorption cooling system in arid areas located in Assiut, Egypt. To achieve the objective of this work, an optimization based on a computer simulation has been performed on the design variables, which are: solar collector area, the volume of the hot storage tank, the volume of the cold storage tank, and thermostat set point of the auxiliary heating element. Economic and environmental evaluations of the proposed systems have been performed as well. A validation of the model results is performed with the experimental results of solar driven silica gel-water adsorption cooling system at Assiut University Campus which has worked since 2012. The results show that the tilt angle of 5 ° for the surface of the solar collectors achieved the best absorbed solar radiation by the collector filed. For all proposed systems, the solar fraction did not affect the volume of the cold water storage tank while it has a significant effect on the area of the solar collector field and as well as the volume of the hot water storage tank. The initial cost of the proposed systems ranges from 2897 €/kWc to 4808 €/kWc and this can be considered as a hindrance to spreading at the commercial level. Meanwhile, the running cost over a year achieves low values, and it ranges from 13.9 €/kWc to 99.11 €/kWc.The proposed systems of lower solar fraction give lower carbon dioxide emissions. The carbon dioxide emissions range from193 kg of $CO_{2eq.}$/kWc per year for the fully solar driven cooling system to 1062 kg of $CO_{2eq.}$/kWc per year for the cooling system fully driven by natural gas. Based on the solar saving approach the proposed system of 24 m^2 solar collector area, 0.6 m^3 hot storage tank, and 1 m^3 cold storage tank with 94 °C auxiliary heater set-point temperature can be considered as the most economically feasible solution.

1. Introduction

The increase in the population activities leads to an increase in the electricity demand which is primarily produced from fossil fuels (coal, oil, and natural gas)representing about 67.4% of the fuel shares of the electricity generation in 2013, according to the international energy agency (IEA) [1]. A part of the electricity consumed in the buildings is used to achieve indoor thermal comfort conditions which are usually done by conventional air conditioning systems. 17% of the overall electricity used worldwide is gone for the refrigeration sector including air conditioning [2]. The air conditioning systems contribution jumps to about 45% of the energy consumption in the residential and commercial building sector [3,4], and it represents more than 70% of building energy consumption for some regions in the Middle East [5].Expanding in the use of the conventional air conditioning systems leads to increase the electricity consumption and thus to fossil fuel shortages and the greenhouse gases as well as the HFC emissions causing depletion of the ozone layer.

Many promising technologies have been used recently in air conditioning systems and for a cleaner environment. In these techniques, renewable energy sources are used as an alternative drive for the air conditioning systems for reducing conventional energy consumption consequently the harmful gas emissions to the environment. Solar assisted cooling has become one of these promising air conditioning technologies, and it has an advantage in hot and arid areas because of the near coincidence of peak building cooling load with the available solar irradiation. Solar-assisted cooling systems are classified into the following main categories: absorption, adsorption, desiccant, and ejector systems which have not been used on the commercial level yet. Till 2009, only 113 large-scale and 156 small-scale solar-assisted cooling systems have been installed all over the world. 92% of these installations are located in Europe. The absorption systems are the most widely used and represent 82%

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Nomenclature

AARE	Average absolute relative error
A_c	Area of the solar collectors, m^2
ARE	Absolute relative error
C_A	Collector area dependent costs, €/m^2
C_E	Collector area independent costs, €
COP	Coefficient of performance
c_p	Specific heat, kJ/kg K
d	Discount rate
G_T	Incident solar radiation upon the collector surface, W/m^2
i	Inflation rate
I_b	Beam incident radiation upon the collector surface, J/h m^2
IC	Initial cost, €
I_d	Diffuse incident radiation upon the collector surface, J/h m^2
I_T	Total incident radiation upon the collector surface, J/h m^2
N	No. of years
n	No. of measurements
PW	Present worth, €
Q	Energy, J
q	Rate of energy, W
$Q_{cd,design}$	Cooling demand of the design day, J
$q_{chiller,rated}$	Rated chilling power of the adsorption chiller, W
$q_{conv,IS}$	Convection heat transfer from internal heat sources within the zone, W
$q_{conv,t}$	Convection heat transfer from all surfaces within the zone, W
$q_{\inf}$	Load due to infiltration heat gain, W
q_{sys}	Heat transfer to the air conditioning system, W
q_{vent}	Load due to ventilation heat gain, W
RC	Running cost, €
SF	Solar fraction
SS	Solar saving, €/kWc
T	Temperature, C̊
V	Volume, m3
X_m	Measured value
X_s	Simulated value

Greek symbols

α_0	Intercept of the solar collector efficiency
α_1	Negative of the first order coefficient, W/m^2 K
α_2	Negative of the second order coefficient, W/m^2 K^2
β	Tilt angle of the solar collector surface, ◦
γ	Surface azimuth angle, ◦
γs	Solar azimuth angle, ◦
ΔT	Temperature difference, C
ηc	Thermal efficiency of the solar collectors
$\eta_{st\&tr}$	Storage and transmission efficiency
θ	Solar incident angle upon the collector surface, ◦
θ_z	Solar zenith angle, ◦
ρ	Density, kg/m^3
ρg	Ground reflectance
τ	Time for meeting the designed daily cooling demand, h

Subscripts

8hrs	8 h around noon
abs	Absorbed
amb	Ambient
aux-set	Set point of the auxiliary heater
avg	Average
cd	Cooling demand
ch	Chilling
chw	Chilled water
cor	Corrected
ct	Cold water storage tank
cw	Cooling water
dh	Driving heat
eco	Eco mode
ht	Hot water storage tank
hw	Hot water in Inlet
m	Mean
out	Outlet
power	Power mode
r	Refers to the proposed cooling system
rej	Rejected
w	Water

of the whole installations and 90% of the small-scale installations, followed by adsorption systems which represent 11% of the whole installations and 10% of the small ones. Meanwhile, the desiccant systems are only used in large installations [6,7]. The solar-assisted cooling systems have a limited share of the air conditioning market worldwide. The higher initial cost of solar assisted cooling technologies is still the main hindrance to bed spread on a wider scale in the residential sector. However, to be competitive for integration in residential buildings, solar-assisted systems have to be as simple as possible to lower their initial cost and implemented along with another application. For example, Causse et al. [8] investigated the possibility to use solar adsorption air- conditioning during summer and direct heating during winter using an enhanced compound parabolic solar collector. Ali et al. [9] presented performance assessment of an integrated cooling plant having both free cooling and solar driven single effect LiBr-water absorption chiller constructed in Oberhausen (Germany). Zhai et al. [10] analyzed the performance of a solar hybrid heating, cooling and power generation system with the silica gel-water adsorption chiller.

The optimization of the solar assisted cooling systems based on energetic, economic, and environmental performance with varying the size of the main system components and the system configuration is required to give a supported design for increasing the competitiveness of the solar-assisted systems in the air conditioning market. In a trial to optimize the solar assisted cooling systems for selecting the best size of the main system components, many types of research have been done. All design optimization trials and techniques for the solar cooling systems have been applied to the solar absorption cooling systems. Ghaddar et al. [11] presented an analytical study of a residential solar Li-Br water absorption cooling system in Beirut, Lebanon. The results showed that for a ton of refrigeration it is required to have a minimum solar collector area of 23.3 m^2 with an optimal hot water storage tank capacity ranging from 1000 to 1500 liters for the system to operate solely on solar energy for about seven hours a day. They also presented an economic assessment based on current cost of conventional cooling systems. They concluded that the solar cooling systems are marginally competitive only when combined with domestic water heating. Fluorides et al. [12] presented a mathematical model and simulation for optimizing a solar assisted absorption cooling system based on weather parameters of Nicosia, Cyprus. The final optimized system parameters were a 15 m^2 compound parabolic collector with a tilt angle of 30◦ a hot water storage tank of 600 l in volume. Assilzadeh et al. [13] presented a simulation model of