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Performance evaluation of solar adsorption cooling systems for vaccine preservation in Sub-Saharan Africa

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HIGHLIGHTS

- A solar adsorption refrigerator was introduced.
- Dynamic behavior of the system was investigated.
- Real climatic data of four Sub-Saharan African sites were considered.
- Best SCOP was predicted in Garoua, Cameroon (0.132).
- Best SCP was reached in Beitbridge, Zimbabwe (3.18 W/kg).

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ABSTRACT

An intermittent solar adsorption refrigerator can supply cold needed in third world countries, especially for vaccine and medicine preservation. This paper investigated theoretically the potential of solar adsorption refrigerators in Sub-Saharan Africa. The dynamic behavior of the system and its performance were assessed using real climatic conditions of four Sub-Saharan African sites. A refrigerator operating with activated carbon/methanol as a working pair was simulated using a 1-D mathematical model to investigate its dynamic optimization. The results showed that the best solar coefficient of performance (SCOP) was predicted in Garoua (Cameroon) and Beitbridge (Zimbabwe). The maximum specific cooling power (SCP) was achieved in Beitbridge (Zimbabwe). Under the climate of Lamu (Kenya), the system presented the lowest performance indices.

1. Introduction

Vaccine-preventable diseases constitute a real threat to the children in some African and other underdeveloped countries. According to the Global Health Observatory (GHO) data [1], approximately 21.8 million infants worldwide were still not being reached by routine immunization services in 2013. The great majority of these children are from Africa. Keeping the vaccines at suitable temperatures is the most serious problem in hot climates. The challenge becomes greater with the non-access to the electricity grid in large areas of many countries. In fact, the estimations of the International Energy Agency indicated that more than one-fifth of the world's population lacked access to electricity in 2010. Among them, 57% live in rural areas in sub-Saharan Africa with no hope to be connected to the grid in the near future [2]. This problem affects significantly the cold supply chain. Kerosene and gas-driven absorption refrigerators have been used for a long time as alternatives. However, they are currently below the minimum standards established by the World Health Organization (WHO) Performance, Quality, and Safety (PQS) system [3]. Furthermore, these devices suffer from the low performance, frequent maintenance, polluting nature of the driven sources and poor temperature control. As a consequence, photovoltaic-powered cooling systems were introduced to sustain the cold chain in remote regions and, therefore, preserve vaccines more efficiently and without polluting the environment [4]. These refrigerators needed batteries to operate during nights. Batteries have relatively short lives compared to the refrigerator lifetime, and then extracosts will be needed along the operation period. As a solution, in some modern configurations of PV cooling units, the batteries were replaced by an ice thermal storage in order to lower a significant portion of the capital and

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Nomenclature

A_s	area (m^2)
c	specific heat at constant pressure (J/kg K)
D	constant in the Dubinin–Astakhov equation
H	bed thickness (m)
I_s	solar radiation (W/m^2)
M	adsorbent mass (kg)
N	number of space nodes (–)
n	constant in the Dubinin–Astakhov equation
P	pressure (Pa)
Q_c	cold production (J)
T	temperature (K)
t	time (s)
W_0	parameter of the Dubinin–Astakhov equation (m^3/kg)
X	methanol concentration inside the adsorber (kg/kg)

Greek letters

λ_{eq}	equivalent thermal conductivity (W/m K)
ρ	density (kg/m^3)
ε	porosity (–)
$\tau\alpha$	transmittance–absorptance product
ΔX	adsorption capacity (kg/kg)
Δt	time step (s)
Δx	space step (m)

Subscripts

a	ambient, adsorbate
ac	activated carbon
c	condenser
e	evaporator
g	gas
w	wall

Abbreviations

SCOP	Solar coefficient of performance
SCP	specific cooling power (W/kg)

maintenance costs [5]. Solar thermal cooling cycles are attractive because they use a clean and renewable energy resource and operate with environmentally harmless refrigerants [6,7]. The current study proposes a solar adsorption cooling unit that can serve as a back-up for the photovoltaic vapor compression system. The solar adsorption unit will produce cold at night without using energy from batteries. This suggestion seems interesting because cold production for solar adsorption takes place during the night.

In the literature, several experimental and theoretical investigations were reported about the analysis of solar adsorption cooling systems for different applications [8,9]. The main objectives of the research contributions focused on the improvement of the system performance, the development of continuous cycles and the assessment of solar adsorption cooling technologies under different climates [10–13]. Alam et al. [14] performed an analytical study of a silica gel/water adsorption cooling system powered with 15 collectors (each 2.415 m^2). The system considered the climatic condition of Tokyo, Japan. The mathematical model assumed that the temperature, pressure, and concentration throughout the adsorbent bed were uniform. Authors reported that the cycle time was the most influential parameter for the adsorption cooling system and suggested to properly optimize the cycle time in order to reduce the number of solar collectors. Ammar et al. [15] simulated a tubular solar collector/adsorber operating under the climate of El Oued (Algeria). The climatic conditions were integrated into the computation procedure using a sinewave form based on maximum and minimum daily temperatures and maximum solar radiation. The optimized system consisted of 1 m^2 double-glazed cover collector filled by 38.59 kg of activated carbon. The proposed design achieved a solar coefficient of performance about 0.21. El-Sharkawy et al. [16] presented a theoretical analysis to assess the performance of solar-powered silica gel/water based adsorption chiller working under different climate conditions of the Middle East region. Real climatic conditions of Cairo and Aswan (Egypt) and Jeddah (Saudi Arabia) were used. The results showed that the use of hot water buffer storage allowed less fluctuating cooling energy production and produced higher average daily cooling capacity and average daily COP. Zhai and Wang investigated a double-bed adsorption chiller operating with Silica-gel/water. The adopted design gave the possibility to switch between two modes: with heat storage and without heat storage. Authors reported that the system without heat storage possessed higher collecting efficiency and could reach comparable performance to the system with heat storage by increasing the collector area [17]. Qasem and El-Shaarawi [18] presented a thermodynamic analysis and a transient modeling study of a solar adsorption ice-maker operating in the city of Dhahran (Saudi Arabia). The results showed that the system performance in winter (5 kg of ice and more per m^2 of collector area) is better than in summer (below 3 kg of ice).

The selection of optimal working pairs is extremely important for the development of solar adsorption cooling systems [19]. Using activated carbon/methanol as a working pair permitted the production of cold at various temperature levels (ice making, refrigeration and air-conditioning) [20]. Furthermore, this couple is efficient, less expensive and could be powered by relatively low temperatures.

To the best of our knowledge, there is no original work dealing with the performance assessment of solar adsorption cooling systems for application in the region of Sub-Saharan Africa despite available solar energy resources and the considerable needs of such systems. The current work proposes the numerical optimization of an activated carbon/methanol solar adsorption cooling unit for vaccine storage in Sub-Saharan Africa. The effects of design parameters and operating conditions on the system's performance were examined as well. The novelties of this work are: (i) The detailed study of a solar adsorption refrigerator with a simple design for vaccine preservation to fulfill a part of the cold needed in off-grid regions, (ii) The investigation of an instantaneous simulation based on real climatic data of four different sites in Sub-Saharan Africa (iii) The resolution approach of the mathematical model considers the variation of the refrigerant's thermophysical properties with the temperature (iv) the evaluation of the system performance for different operating and design options. It is also important to note that the proposed mathematical model gives accurate dynamic behavior of the adsorber since the temperature and methanol concentrations are time and space dependents.

2. System description

2.1. Adsorption cycle

The basic cycle of a solar adsorption cooling system consists of four phases as shown in Fig. 1 [9].