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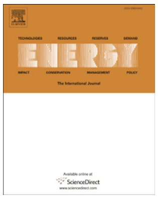

Thermodynamic analysis and theoretical study of a continuous operation solar-powered adsorption refrigeration system

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ABSTRACT

Due to the intermittent nature of the solar radiation, the day-long continuous production of cold is a challenge for solar-driven adsorption cooling systems. In the present study, a developed solar-powered adsorption cooling system is introduced. The proposed system is able to produce cold continuously along the 24-h of the day. The theoretical thermodynamic operating cycle of the system is based on adsorption at constant temperature. Both the cooling system operating procedure as well as the theoretical thermodynamic cycle are described and explained. Moreover, a steady state differential thermodynamic analysis is performed for all components and processes of the introduced system. The analysis is based on the energy conservation principle and the equilibrium dynamics of the adsorption and desorption processes. The Dubinin–Astakhov adsorption equilibrium equation is used in this analysis. Furthermore, the thermodynamic properties of the refrigerant are calculated from its equation of state. The case studied represents a water chiller which uses activated carbon–methanol as the working pair. The chiller is found to produce a daily mass of 2.63 kg cold water at 0 °C from water at 25 °C per kg of adsorbent. Moreover, the proposed system attains a cooling coefficient of performance of 0.66.

1. Introduction

The traditional vapor compression machines are dominating electricity consumers and their operation cause high electricity peak loads. Therefore, providing cooling by utilizing a green source of energy is the key solution to both global energy and environmental pollution problems. The solar energy comes at the top of the green energy sources list. That is due to the abundance and to some extent equal distribution of the solar radiation in nature compared with other types of renewable energy [1]. Recently, solar-powered cold production systems attract many researchers because the peaks of requirements in cold coincide most of the time with the availability of the solar radiation [2].

The booming progress in the field of green cooling technology offers a considerable number of solar-powered refrigeration systems as alternatives to the conventional vapor compression refrigeration machines. One of these technologies is the solar-powered adsorption refrigeration (SAR) system. The refrigerants used in SAR systems are environmentally benign and natural which have zero ozone depleting as well as a zero global warming potentials. The most widely used working pairs are activated carbon–methanol [3–8], activated carbon fibers-methanol [9], activated carbon-ethanol [10], activated carbon-ammonia [11], silica gel–water [12], and zeolite-water [13]. The activated carbon–methanol is a suitable working pair to be used in SAR systems. That is because, methanol has low desorption temperature, low adsorption/desorption heat and relatively high evaporating latent heat. Moreover, the active carbon based adsorption systems has the highest COP if methanol is used as a refrigerant [14].

The basic SAR system is a single adsorption bed which is integrated with a solar collector. A flat plate adsorption refrigeration ice maker has been built for demonstration purposes using activated carbon–methanol pair [15]. The adsorption solar refrigerator designed and constructed by Anyanwu and Ezekwe [16] has a flat plate type of effective exposed area of 1.2 m^2. The experimental results for a silica gel–water tubular reactor integrated with 2 m^2 double glazed flat plate collector give a gross solar cooling coefficient of performance of 0.19 [17]. Collector types other than the

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Nomenclature

$\mathcal{X}^*$	adsorbed phase concentration ratio at equilibrium [kg/kg]
q_{sh}	isosteric heat of adsorption or desorption [J/kg]
W_o	the maximum adsorption capacity [m^3/kg]
C	specific heat [J/kg.K]
D	constant in Dubinin–Astakhov equation [–]
E	energy [J]
h	the specific enthalpy [J/kg]
L	latent heat of vaporization [J/kg]
m	mass [kg]
n	constant in Dubinin–Astakhov equation [–]
P	pressure [Pa]
Q	thermal energy [J]
R	gas constant [J/kg.K]
T	temperature [K]
U	total internal energy [J]
u	the specific internal energy [J/kg]
V	volume [m^3]
W	work [J]
y	wetness fraction [–]

Greek symbols

ρ	density [kg/m^3]
θ^*	the adsorbate phase volume fraction at equilibrium [–]
ε	porosity of the solid adsorbent medium [–]

Superscripts

$1 \rightarrow 2$	the isosteric pre–heating process
$2 \rightarrow 3$	the isobaric desorption process
$3 \rightarrow 4$	the isosteric cooling process
$4 \rightarrow 1$	the adsorption process

Subscripts

a	adsorbate phase
ads	adsorption
amb	ambient or atmospheric
b	bed
con	condenser or condensation
des	desorption
eff	effective
ev	evaporator
f	fluid or liquid
g	gas or vapor phase
max	maximum
mc	metallic cover
min	minimum
sat	saturation
sh	heat of adsorption/desorption
sm	solid or porous media

Abbreviations

CO-SAR	continuous operation solar-powered adsorption refrigeration
COP	coefficient of performance [–]
CP	cooling power [W]
CTAR	constant temperature adsorption refrigeration
RCV	refrigerant control valve
SAR	solar-powered adsorption refrigeration
SCP	specific cooling power [W/kg]

conventional flat plate have been used with the SAR system [18–20]. The basic one bed cooling system has been subjected to many modifications and developments to increase and enhance the system performance. Many authors presented experimental studies [16,21–23] as well as theoretical and simulation work [3,11,24–27].

In spite of these efforts, the continuity of cold production from the SAR system is still a major issue. This is because, the adsorption reactor of the basic SAR system is discharged from the refrigerant vapor during the sunrise time. The re-charging process and therefore the associated cold production at the evaporator side take place during the night time only. In this regards, the present study introduces a simple SAR system that is able to produce cold continuously during the whole day time. The thermodynamic analysis of the proposed continuous operation solar-powered adsorption refrigeration (CO-SAR) system is developed and presented as well.

2. System description, operation procedure, and the theoretical thermodynamic cycle

The suggested CO-SAR machine is shown schematically in Fig. 1. The system is simple in construction and consists of the following components:

1. A flat plate solar collector installed in a movable supporting frame and has the ability to rotate around a rod in the frame.
2. Two adsorption reactors (RI and RII), condenser, and evaporator.
3. A refrigerant collecting and storage container.
4. A refrigerant control valve, RCV, which is a one-way valve used to control the refrigerant liquid flowing to the evaporator.
5. Two one-way gas pressure regulators connecting the adsorption beds with the evaporator; IE and IIE. The main function of these gas regulators is to maintain a constant pressure inside the evaporator.
6. Two one-way valves connecting both of the adsorption beds with the condenser; IC, IIC.
7. A throttling device which is fixed on the pipeline between the RCV and the evaporator.

The two reactors are identical, having the same dimensions and containing the same mass and type of the adsorbent. A thermal insulating material is placed in between the two adsorption beds in

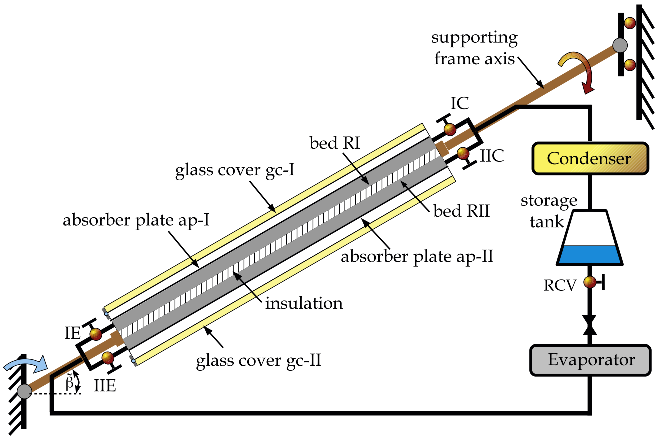

Fig. 1. Schematic representation of the proposed CO-SAR system.