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Modeling of a thermal adsorber powered by solar energy for refrigeration applications

A. Allouhi [a], T. Kousksou [b, *], A. Jamil [a], Y. Zeraouli [b]

[a] École Supérieure de Technologie de Fès, Université Sidi Mohamed Ibn Abdelah, Route d'Imouzzer, BP 2427, Morocco
[b] Laboratoire des Sciences de l'Ingénieur Appliquées à la Mécanique et au Génie Electrique (SIAME), Université de Pau et des Pays de l'Adour, IFR, A. Jules Ferry, 64000 Pau, France

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ABSTRACT

In this paper, we introduce a dynamic model of a thermal adsorber powered by solar energy. The system operates with silica gel (as an adsorbent) and water (as a refrigerant). The Finite Difference approximation was used; the obtained numerical model was then incorporated in a MATLAB code in order to solve the system of algebraic equations modeling heat and mass transfers. The real ambient temperature and solar radiation variations relative to a typical summer day in Fez (Morocco) are taken into account. The system is characterized by its simple design and can reach a SCOP (Solar Coefficient of Performance) of 0.15 under a condenser and evaporator temperatures of 27 °C and 5 °C respectively. Consequently, this installation can be an attractive solution to meet positive cooling needs (medicine and food storage) in off-grid electricity regions. It can be also proposed in humanitarian actions in Africa.

1. Introduction

Cooling applications are causing extremely high energy consumption with a harmful effect on the environment [1–4]. As a solution, the current international policies are oriented towards using renewable energies to insure the relative human needs during summer periods [5–7]. The use of solar energy as a driven source in cooling systems appears a very attractive solution, since the cold demand coincides most the time with the solar irradiation availability [8–10]. Although both thermal and electric paths were exploited, thermal cooling technologies are more suitable than the PV (photovoltaic)-based ones because they can use more incident sunlight. Accordingly, in the few recent years, solar thermal processes mainly adsorption and absorption have been the subject of significant research and commercial development [11–13].

Over conventional vapor-compression systems, such technologies have the advantage of using cleaner refrigerants and using a free abundant energy source.

Currently, the state of the market is characterized by the domination of absorption machines. In fact, they have lower cost and are slightly more efficient than adsorption machines. However, adsorption cycles can be more advantageous for the following positive features [14,15]:

- Adsorption cooling systems can accommodate a wide range of heat source temperatures (50 °C–500 °C) without producing any corrosion unlike absorption systems in which corrosion occurs above 200 °C.
- The system is noiseless, where there are not many moving parts.
- Adsorption machines are characterized by their simple control and the absence of vibrations.
- They use solid sorbents and hence they are preferred for conditions with serious vibration and shocks, like in fishing boats and locomotives.
- Most refrigerants have zero ODP (ozone depleting potential) and little GWP (Global Warming Potential)
- The adsorption system has a simpler design compared to the absorption system in which many additional equipments are required. For example, in the case of the ammonia/water working pair, an extra rectifier is needed before the condenser to supply pure refrigerant.

Furthermore, solar adsorption technology can offer CCHP system (combined cooling, heating and power generation) in domestic, commercial and industrial sectors [16].

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* Corresponding author.
E-mail address: Tarik.kousksou@univ-pau.fr (T. Kousksou).

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Nomenclature

A	area [m^2]
c	specific heat at constant pressure [J kg^{-1} °C^{-1}]
D	constant in the Dubinin–Astakhov equation
H	height of the adsorbent bed [m]
I	solar radiation [W m^{-2}]
M	mass [kg]
N	node number of space discretization
n	constant in the Dubinin–Astakhov equation
P	pressure [Pa]
T	temperature [°C]
t	time [s]
W_0	constant in the Dubinin–Astakhov equation
X	adsorbed mass of adsorbate per mass of adsorbent [kg kg^{-1}]

Greek letters

λ_{eq}	equivalent thermal conductivity
ρ_i	density [kg m^{-3}]
ε	porosity
τ	solar transmission coefficient of the collector
α	absorbance of the collector
ΔX	adsorption capacity [kg kg^{-1}]
Δt	time step [s]

Subscripts

a	adsorbate
ads	adsorption
amb	ambient
c	condenser
e	evaporator
eq	equivalent
max	maximum
min	minimum
s	solar
sa	saturated
sl	silica gel
sr	sunrise
ss	sunset
w	wall

Abbreviations

SCOP	solar coefficient of performance

The major challenge of such system is to increase the efficiency and reduce initial cost in order to compete with the traditional vapor compression systems. Another challenge is to overcome the cycle discontinuity.

The most widely used couples in adsorption cycles are: activated carbon–ammonia [17,18], activated carbon–methanol [19], activated carbon fiber–ethanol [20] and zeolite–water [21]. Using silica gel/water as a working pair has attracted much attention, especially in the last two decades, due to its environmentally friendly refrigeration that can be powered by low grade heat source [22]. In this paper, a dynamic simulation of a small adsorption cooling unit using an integrated thermal collector–adsorber is investigated in order to meet positive cooling need in off-grid electricity regions. The system performance is also predicted for different operating conditions. At the end, concluding remarks and future perspectives are drawn.

2. System description

In the adsorption cooling system, a thermal adsorber replaces the electric compressor of a basic vapor compression machine. The rest of the machine is generally unmodified (Fig. 1(a)). The reactor consists of a transparent cover, a lateral and rear insulation and a rectangular sheath in steel containing a porous medium having the ability to adsorb and desorb the refrigerant (Fig. 1(b)). In the current work, the proposed configuration is characterized by a simple design, low material cost and no harmful effect on the environment because the refrigerant is water. The refrigerator is designed to cool a small chamber for medicine or food storage in off-grid electricity regions with tropical or arid climate.

The ideal adsorption cycle is shown in Fig. 2 and is constituted of four phases:

- Isosteric heating phase: Pressurization process at a constant volume.

In the morning, state 1 (T_a, P_e), cold production comes to take place. The adsorber is fully charged with the refrigerant and is apart from both the condenser and the evaporator by valves 1 and 2. The received heat from the solar collector causes a gradual increase of

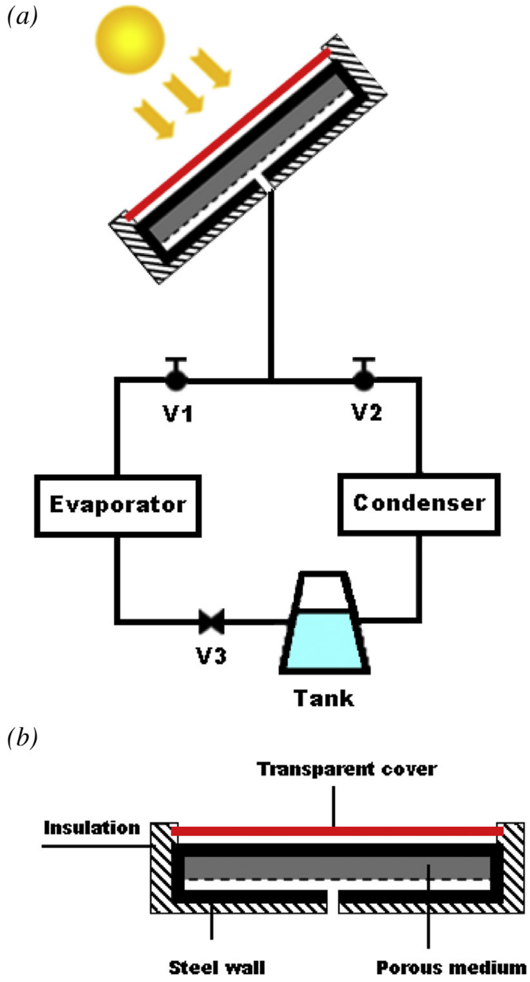

Fig. 1. (a) Schematic diagram of the solar adsorption cooling system, (b): reactor sketch.