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Development of a continuously operating solar-driven adsorption cooling system: Thermodynamic analysis and parametric study

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ABSTRACT

A novel solar-driven adsorption cooling system that is able to produce cold continuously along the 24-h of the day is proposed in this study. The working principle of the proposed system is based on the constant temperature adsorption cooling cycle which is introduced also in this work. Both of the cooling system principle of operation and the cycle description are explained in details. Moreover, complete thermodynamic analysis is performed for all components of the system as well as processes of the theoretical cycle. Activated carbon-methanol is used as the working pair in the case studied. Furthermore, a parametric study of the influence of many system parameters on the performance is accomplished and discussed as well.

1. Introduction

Energy is considered the continuous driving power for economic growth and the major requirement for technological developments. The increasing rate of population, industry, and the per capita energy consumption are the major forces that cause the increase in energy demand during the coming years. However, the conventional energy types are neither reliable nor sustainable and the world's reserves of oil are not large enough to be dependable in the near future. As a consequence, securing sustainable and renewable resources of energy with reasonable costs and without adverse impacts on our environment are the challenge. From this point, solar energy comes at the top of the list due to its abundance and more equal distribution in nature than other types of renewable energy. There are currently several rapid expanding technologies that are used to harness the sun's power. These include power generation, solar water heating and desalination, cooking and food drying, space heating, cooling and refrigeration, and others.

Cooling, refrigeration, and air conditioning processes mainly contribute in a considerable number of fields of human life. However, the traditional vapor compression machines are dominating electricity consumers and their operation and propagation cause high electricity peak loads during the summer, especially in those countries with tropical climate. The energy consumption for air conditioning systems has recently been estimated to be 45% of the whole households and commercial buildings, Choudhury et al. [1]. That is besides, the conventional vapor compression systems use non-natural refrigerants that have high global warming as well as ozone layer depletion potentials due to the fluorocarbons. Consequently, Providing cooling by utilizing a green energy such as solar energy is the key solution to both energy and pollution problems. The Mediterranean countries may save 40–50% of their energy used for air conditioning by implementing solar-driven air conditioning systems, Balaras et al. [2] and Abu Hamdeh and Al-Muhtaseb [3].

The development of solar refrigeration technologies became the worldwide focal point for concern because the peaks of requirements in cold coincide most of the time with the availability of the solar radiation. One of these mature technologies is the solar powered adsorption refrigeration technology which is proven to be suitable and applicable for refrigeration as well as air conditioning applications. The refrigerants used in these systems are environmentally benign, natural refrigerants and are free from CFC. Therefore, these systems have zero ozone depleting as well as

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Nomenclature

C	Specific heat, [$Jkg^{-1}K^{-1}$]
C_p	Specific heat at constant pressure, [$Jkg^{-1}K^{-1}$]
C_υ	Specific heat at constant volume, [$Jkg^{-1}K^{-1}$]
X	Concentration ratio, [−]
$\dot{m}$	Mass flow rate, [kgs^{-1}]
COP	Coefficient of performance, [−]
h	Enthalpy, [Jkg^{-1}]
L	Latent heat, [Jkg^{-1}]
m	Mass, [kg]
P	Pressure, [Pa]
Q	Heat energy, [J]
R	Gas constant, [$Jkg^{-1}K^{-1}$]
T	Temperature, [K]
V	Volume, [m^3]
y	Wetness fraction, [−]

Greek letters

$\in$	Porosity of the solid adsorbent medium, [-].
ρ	Density, [kgm^{-3}].
θ	Adsorbate volume fraction, [−].

Subscripts

g	Gas or vapor phase.
hp	Heat pump.
a	Adsorbed phase.
amb	Ambient.
b	Bed.
con	Condenser.
ev	Evaporator.
f	Fusion.
max	Maximum.
mc	Metallic shell.
min	Minimum.
pm	Porous media.
R	Refrigeration.
s	Saturation.
sh	Heat of adsorption/desorption.
w	Water.

a zero global warming potentials. The most widely used working pairs in the adsorption cooling systems include activated carbon-methanol [4], activated carbon fibers-methanol [5], activated carbon-ethanol [6], activated carbon-ammonia [7], silica gel-water [8], and zeolite-water [9].

The basic one-bed adsorption cooling system is intermittent in operation and has a low performance. Extensive researches have been introduced in order to obtain a continuous operation and a better performance of the system by using the multi-bed technology. These advanced multi-bed systems include many operation schemes like the internal vapor mass recovery cycle [10–12], heat recovery regeneration cycle [13–19], thermal wave heat regeneration cycle [20–24], convective thermal wave cycle [25–28], the cascaded cycle [29–33], and the multi-stage systems [34–37]. However, these advanced multi-bed schemes require a continuous supply of driving heat to produce a continuous operation. Therefore, the use of solar energy, which is intermittent by nature, as a power source for driving the adsorption cooling system results in an intermittent operation even if a multi-bed scheme is used. That is why solar powered adsorption refrigeration systems are still using the basic single-bed scheme. In this case, the adsorption bed is integrated with the solar collector and the system provides cold only during the night period. Many researches have been introduced, both theoretically and experimentally, to study the solar-driven single-bed basic adsorption refrigeration system. A flat plate solid-adsorption refrigeration ice maker has been built for demonstration purposes using activated carbon/methanol pair, Li et al. [38]. The adsorption solar refrigerator designed and constructed by Anyanwu and Ezekwe [39] has a flat plate type collector/generator/adsorber 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 COP of 0.19, Hildbrand et al. [40]. Collector types other than the conventional flat plate have been used with the solar adsorption heat pumps. A compound parabolic concentrator solar collector has been used, [41–43]. The performance of the solar refrigerator is studied experimentally by many authors, [39,44–46]. Moreover, theoretical and simulation work has been extensively presented in literature, [4,7,47–50].

As discussed above, solar powered adsorption cooling systems produce cold only at the period of night. However, most of air conditioning, cooling, and refrigeration demands are needed during the day time, when the ambient temperature is high, as well as at the night periods. According to our best knowledge, there is no study in the literature that explains the possibility of cold production using a continuous operation solar-driven adsorption cooling system along the whole day. As a consequence, we introduce in the present study a novel and a simple solar-driven adsorption cooling system that is able to produce cold during the whole 24 h of the day.

2. The system and cycle description

The proposed solar powered adsorption cooling system for continuous cold production is shown schematically in Fig. 1. This system is composed of four heat exchangers; two adsorption reactors RI and RII, a condenser, and an evaporator. That is besides a refrigerant storage container, two gas regulators connected to the evaporator (1E, 2E), two one-way valves connected to the condenser (1C, 2C), and a throttling device between the refrigerant tank and the evaporator. The reactor contains a type of solid

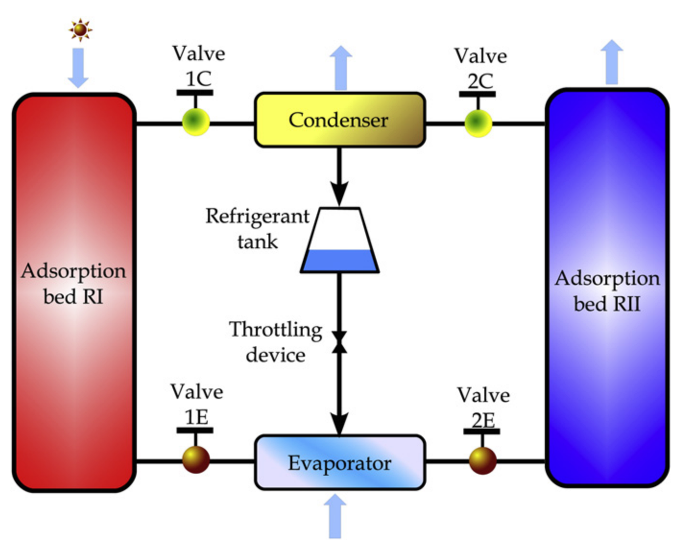

Fig. 1. Schematic diagram of the constant temperature adsorption cooling cycle.