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Thermal analysis and modeling study of an activated carbon solar adsorption icemaker: Dhahran case study

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ABSTRACT

Intermittent adsorption refrigeration systems are suitable for producing ice in remote areas. EES and MATLAB computer programs are exploited to analyze the thermodynamic cycle and to model the system under Dhahran climate conditions, respectively. The results show that the system performance in winter is better than in summer under the climate conditions for the city of Dhahran, Saudi Arabia. For example, the system produces below 3 kg in the hot days and more than 5 kg of ice per square meter of solar collector in the cold days with solar coefficient of performance (SCOP) that varies between 0.077 and 0.17, respectively.

1. Introduction

Refrigeration and air conditioning demands are widely increasing because of the increase in population as well as the standard and comfort of living and the dramatic growth of industries. The majority of the cooling systems are driven by electric energy while electricity may not cover all the human living areas such as a countryside of some developing countries. Therefore, people living in such areas may not be able to preserve their food and store vaccines in their local clinics. Accordingly, solar adsorption refrigeration technology has attracted some research interests since 1990 because it is clean and simple for use in air conditioning, ice making, food preservation and vaccine storage. The idea of these devices is the reversible physical sorption of a vapor on the surface of a porous solid (desorption of the refrigerant when exposed to heat and adsorption of it during cooling). An intermittent adsorptive solar icemaker is an attractive application that is composed of adsorbent bed as adsorptive reactor integrated into a solar collector for desorption of the sorbent material during the day. During the night, adsorption occurs by the adsorbent bed when the refrigerant comes back from the evaporator, in which the cooling effect is obtained and some ice may be produced.

The important working pairs studied in the literature as absorbent/adsorbate for adsorption cooling were investigated and compared by Critoph [1], San and Lin [2] and Wang et al. [3]. Additionally, Askalany et al. [4] revised several refrigerants that work with carbon adsorbent while a lot of adsorption refrigeration materials are carefully reviewed by Alghoul et al. [5].

Activated carbon with methanol as a working pair is broadly used in adsorption refrigeration due to the large adsorption quantity and low desorption heat, which is about 1800–2000 kJ kg^{-1} [4]. The adsorbent (solid porous material) properties indicate that the activated carbon is a good choice for adsorption cooling because of its high capacity for desorption and adsorption reaches 0.45 kg kg^{-1} [6]. Moreover, the system of activated carbon methanol needs low grade heat source, which is suitable to work by solar energy. Actually, the activated carbon exists in several forms such powders, granulated, molecular sieves and carbon fibers, Srivastava and Eames [7]. On the other hand, methanol operates at sub atmospheric pressure; the low-pressure systems require a good manufacturing for avoiding leakage, which significantly affects the performance and can shut down the system working. Another deficiency is that the methanol is not compatible with copper at temperatures greater than 120 °C [5] and it decomposes at 150 °C to formaldehyde (HCHO) or dimethyl ether (CH_3OCH_3) by the mechanism of dehydrogenation or dehydration [8]. The decomposition reaction of methanol with aluminum alloy is greater than the copper [8].

Many researches in the literature conducted with adsorption refrigeration through either theoretical analysis or prototypes experimental works or the both. Theoretical and experimental heat and mass transfer in an adsorbent bed for a flat plate solar adsorption icemaker were studied by use 10 kg of Methanol and 42 kg of activated carbon in a rectangular adsorbent bed of 1.5 m^2 solar

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Nomenclature

A	area (m^2)
COP	coefficient of performance
C	specific heat ($J\ kg^{-1}\ K^{-1}$)
C_p	specific heat at constant pressure ($J\ kg^{-1}\ K^{-1}$)
C_v	specific heat at constant volume ($J\ kg^{-1}\ K^{-1}$)
D	Dubinin–Astakhov constant (K^{-1})
$D1$	diameter of inner pass tube (m)
$D2$	internal diameter of absorber tube (m)
$D3$	external diameter of absorber tube (m)
D_o	surface diffusion coefficient ($m^2\ s^{-1}$)
E_a	activation energy of surface diffusion ($J\ mol^{-1}$)
i	specific enthalpy ($J\ kg^{-1}$)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
H	heat of desorption or adsorption per unit mass of methanol ($J\ kg^{-1}$)
I_T	incident solar radiation ($W\ m^{-2}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
K	adsorbent constant
L	latent heat ($J\ kg^{-1}$)
L_c	collector length (m)
L_t	absorber tubes length (m)
M, m	mass (kg)
m_m	methanol uptake (kg)
n	Dubinin–Astakhov constant
N_g	number of glass cover
n_{tube}	number of absorber tubes
P	system pressure (Pa)
Q	heat amount (J)
R	gas constant ($J\ mole^{-1}\ K^{-1}$)
r	radius (m)
$R1$	radius of inner pass tube (m)
$R2$	internal radius of absorber tube (m)
$R3$	external radius of absorber tube (m)
r_p	average radius of adsorbent particles (m)
SCOP	solar coefficient of performance
SCP	specific cooling power ($W\ kg^{-1}$)
T	temperature (°C or K)
t	time (s)
U	overall heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
V_w	wind velocity ($m\ s^{-1}$)
W_c	collector width (m)
w	maximum limit of mass adsorbed ($L\ kg^{-1}$)
x	concentration ratio of adsorbate inside adsorbent ($kg\ kg^{-1}$)

Greek symbols

δ	thickness (m)
Δ	difference/change
τ	transmittance
α	absorptivity
ε	emissivity
σ	Stefan Boltzmann constant ($W\ m^{-2}\ K^{-4}$)
β	collector tilt angle (°)
ρ	density ($kg\ m^{-3}$)

Subscripts

1, 2, 3, 4	processes terminal locations
ac	activated carbon
a	adsorption
amb	ambient
b	back
c	condenser
casing	evaporator insulation casing
collector	solar collector
d	desorption
e	evaporator
eff	effective
eq	equivalent
gas	gas phase
g	generation/glass
i	insulation
ice	ice
in	inside
is	collector side insulation
L	collector overall
liquid	liquid phase
m	methanol
max	maximum
metal	tubes metal
min	minimum
o	maximum limit related to sorption amounts
out	outside
pw	absorber plate wall
s	side
sa	starting adsorption
sat	saturated
sd	starting desorption
sol	solidification
t	top
w	water
wm	water tank metal

Superscript

°	degree

collector [9]. The results showed that the numerical results were in good agreement with experimental study at SCOP of 0.125 and 0.132 for 30.24 and 29 MJ of incident solar radiation, respectively. Constructed 0.8 m^2-solar-adsorption icemaker, Medini prototype [10] showed 4.2 kg of ice per day could be obtained with a SCOP equals 0.15 under Tunisia weather conditions. Activated carbon/methanol was used to introduce a mechanical and experimental freeze proof solar adsorption cooling tube [11]. The collector was constructed as outer tube, center tube and vacuum tube that were made of hard borosilicate glass. The maximum temperature generated by the system was about 110 °C whereas the evaporator temperature reached −4 °C. The device achieved 87–99 kJ of cooling capacity and a SCOP of 0.11. The effective thermal conductivity of the adsorbent bed and the system pressure are assumed as variable parameters [12] via a theoretical simulation of a solar adsorption refrigeration. The results showed that the change in the effective thermal conductivity of reactor is very small (between 0.5 and 0.528 $W\ m^{-1}\ K^{-1}$) and the system pressure during adsorption and desorption processes was almost constant. The maximum solar coefficient of performance reached was 0.2 under Canada's climate on 30 June 2009. Another research [13] simulated activated carbon/methanol adsorptive icemaker according to climatic conditions of Messina, Italy (38° 12′ N, average useful solar radiation was about 520 $W\ m^{-2}$ for June and about 250 $W\ m^{-2}$ for December). It used a flat plate solar collector of 1.5 m^2 that contained 13 concentric tubes filled with 37 kg of activated carbon and about 10.5 kg of methanol. For the most part of the year (from April to October), a daily ice production of 5 kg could be produced. This amount decreased to 4 kg in February and March. The coldest months in the year (January, November and December) had the