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Simulation of a solid sorption ice-maker based on the novel composite sorbent "lithium chloride in silica gel pores"

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ABSTRACT

In this paper, a novel composite sorbent "lithium chloride in silica gel pores" is proposed for application in solar-powered adsorptive ice makers. A mathematical model was used in order to calculate the performance of an ice-maker using this material as adsorbent and methanol as adsorbate. The results of the model showed that a maximum solar coefficient of performance (COPs) of 0.33 and a maximum daily ice production (DIP) of 20 kg m^{-2} can be obtained for an ice-maker equipped with a solar collector area of 1.5 m^2 and 36 kg of adsorbent material. Such performance are noticeably higher than those obtained using commercial activated carbon, that is the adsorbent mostly proposed till now.

1. Introduction

A solar-powered adsorptive ice-maker consists of a small size adsorbent reactor connected to a solar collector, for regeneration of the sorbent material during the day, and connected to an evaporator, for ice production during the night [1,2]. Different prototypes were realized, showing the potentiality of this technology [2–5].

In particular, Sumathy and Li [2,3] designed and tested in Hong Kong a solar adsorption ice-maker with a single flat-plate collector (0.92 m^2 exposed area), based on activated carbon/methanol pair. Their experiments showed that this system can produce 4.3–5.4 kg m^{-2} day^{-1} of ice, with a solar COP of 0.10–0.12. These values are in good agreement with those reported by Li [4] for a similar flat-plate ice-maker tested in Shanghai: 4.7–6.7 kg m^{-2} day^{-1} of ice and a COP of 0.12–0.15, for a solar collector of 0.75 m^2. Anyanwu and Ezekwe [5] designed, constructed and tested in Nsukka, Nigeria, a flat-type solar adsorption refrigerator using activated carbon/methanol, with effective exposed area of 1.2 m^2. They obtained a maximum solar COP of 0.02, but this low value was attributed to the "non-selective collector plate surface coating used". Recently, Khattab [6] proposed and tested an innovative modular ice-maker with the adsorbent (granular carbon bonded with blackened steel) placed in a glass container, positioned between reflector panels. This system, using methanol as adsorbate, provided a COP of 0.16 and a daily ice production of 9.4 kg m^{-2} day^{-1}. Wang and Wang [7] reported a COP of 0.18 for a sophisticated two-bed adsorption prototype ice-making machine operating with heat and mass recovery and based on activated carbon/methanol pair.

Several authors estimated the performance of adsorption ice-makers by mathematical modelling [8–13]. The solar COP and the DIP calculated by simulations ranged between 0.10–0.12 kg m^{-2} day^{-1} and 4–10 kg m^{-2} day^{-1}, respectively. Such results are in good agreement with those obtained by testing experimental prototypes.

It must be pointed out that most of the ice-makers presented in literature use conventional activated carbon as adsorbent. The adsorption capacity of activated carbons is rather low and usually does not exceed 30–40 wt.%.

The utilization of novel adsorbent materials with improved methanol sorption ability can be an efficient way to increase the performance of the system. Recently, the Boreskov Institute of Catalysis, Novosibirsk, Russia in collaboration with the CNR-ITAE, Messina, Italy, developed a new class of methanol composite sorbents [14,15]. This new class of sorbents is directly derived by the SWSs (selective water sorbents; i.e. composite materials consisting of "inorganic salts confined to porous matrices"), that have already been proposed for water vapour sorption [16]. The synthesised composite sorbents demonstrated a strong affinity to methanol. Indeed, the maximal amount of methanol sorbed w_{max} = 75–80 wt.% exhibited by some composites is much higher than the methanol sorption capacity of conventional activated carbons [17]. This great enhancement of adsorptivity is due to the high contribution of methanol absorption by the salt embedded in the silica gel porous matrix (see [15] for details). Among the

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Nomenclature

A_i (i = 1–5, 9)	heat transfer surface (m^2)
c	specific heat (J kg^{-1} K^{-1})
COPs	solar coefficient of performance
DIP	daily ice production (kg)
I_β	available solar radiation at $\beta = 30°$ (W m^{-2})
K_i (i = 1–3)	flag: 0 or 1 (see Eqs. (2) and (9))
L_a	adsorbate latent heat of condensation/evaporation (J kg^{-1})
L_w	water latent heat of solidification (J kg^{-1})
m	mass (kg)
m_a	initial adsorbate mass inside evaporator (kg)
m_w	liquid water mass (kg)
n	solar collector area (m^2)
p	pressure (Pa)
T	temperature (K)
t	time (s)
t_{cycle}	cycle time (s)
U_i (i = 1–9)	global heat transfer coefficient (W m^{-2} K^{-1})
w	uptake (kg kg^{-1})

Greek letters

$(\tau\alpha)_{eff}$	transmittance/absorptivity coefficient
ΔH	adsorption/desorption enthalpy (J kg^{-1})
ΔT	variation of temperature (K)
Δw	variation of uptake (kg kg^{-1})

Subscripts

1	solar collector/environment
2	solar collector/adsorbent
3	condenser/environment
4	evaporator/liquid water
5	environment/liquid water
6	evaporator/phase-changing water
7	evaporator/solid water
8	environment/solid water
9	evaporator/environment
a	adsorbate
ads	adsorption
amb	ambient
c	condenser
des	desorption
eq	equivalent
ev	evaporator
ice	iced water
lw	liquid water
m	solar collector
s	solid adsorbent material (dry)
w	water
β	tilt angle

Superscripts

C	closed ventilation windows
O	open ventilation windows

different composites synthesised, the sorbent "lithium chloride in mesoporous silica gel" (2–50 nm pore diameter) appeared to be the best candidate for sorption cooling driven by a low temperature energy source [18].

The aim of this paper is to evaluate the performance of a solar-powered adsorptive ice-maker using the novel composite "lithium chloride in mesoporous silica gel" by applying the simulation tool presented in Ref. [19].

The model makes it possible to calculate the performance of the unit in terms of solar coefficient of performance (COPs), daily ice production (DIP) and equivalent daily ice production (DIP$_{eq}$). The obtained performance are compared with those corresponding to the commercial adsorbent activated carbon AC35. In the first part of the paper, the main features of the composite sorbent and of the simulated adsorptive unit are presented. Then, performance of the adsorptive ice-maker are calculated.

2. Main features of the composite sorbent "lithium chloride in mesoporous silica gel"

The composite sorbent "lithium chloride in mesoporous silica gel" (salt content 29.5 wt.%) was synthesised by impregnation of silica gel Grace Davison 8926.02 (average pore diameter $d_{av} = 15$ nm, specific surface $S_{sp} = 326$ m^2 g^{-1}, pore volume $V_p = 1.5$ cm^3 g^{-1}) with an aqueous solution of lithium chloride. More details on the synthesis procedure were presented by Gordeeva et al. [15]. Fig. 1 shows the basic thermodynamic cycles for an adsorption air conditioner ($T_{ev} = 10$ °C, $T_c = T_{ads} = 35$ °C, $T_{des} = 80$ °C) and an ice-maker ($T_{ev} = -2$ °C, $T_c = T_{ads} = 30$ °C, $T_{des} = 80$ °C) using the composite "lithium chloride in mesoporous silica" and the commercial activated carbon AC35.

The cycles are plotted over an isosteric diagram that was obtained from the experimental equilibrium data presented in Refs. [15,20] (only the significant isosters are plotted). It is evident that this novel composite sorbent presents an outstanding variation of methanol uptake per cycle ($\Delta w = 46$ wt.% and 18 wt.% for air conditioning and ice-making, respectively), which is much larger than those of the conventional carbon AC35 ($\Delta w = 11$ wt.% and 9 wt.% for air conditioning and ice-making, respectively). This is a convenient feature, because the performance of adsorptive machines increase when the amount of cycled working fluid increases [17].

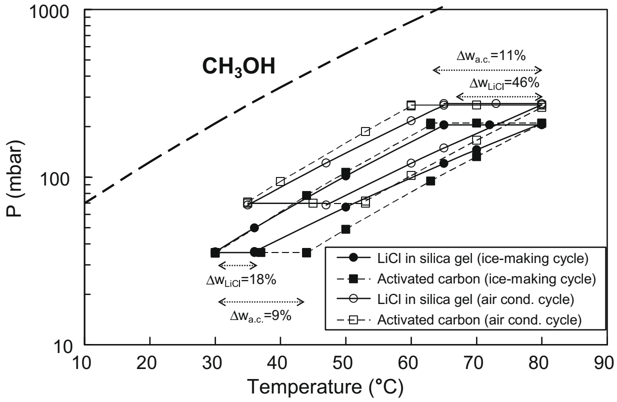

Fig. 1. Comparison between the composite sorbent "lithium chloride in mesoporous silica gel" and the activated carbon AC35, in terms of air conditioning and ice-making cycles.

The stability of adsorbent is of primary importance for evaluation of practical potential. Study on the phase composition, porous structure, and sorption properties of both the fresh and tested composites showed that no significant change, in composite structure and sorption ability, occurs during the cycling. Further details can be found in [21].

Furthermore, the stability to the cyclic treatment has been verified for this typology of materials [22]. A stability of the porous