Energy Conversion and Management 49 (2008) 3025–3035

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

An adsorptive solar ice-maker dynamic simulation for north Mediterranean climate

S. Vasta [a], G. Maggio [a,*], G. Santori [b], A. Freni [a], F. Polonara [b], G. Restuccia [a]

[a] CNR – Istituto di Tecnologie Avanzate per l'Energia "Nicola Giordano", Via Salita S. Lucia sopra Contesse 5, 98126 Santa Lucia, Messina, Italy
[b] Università Politecnica delle Marche, Facoltà di Ingegneria, Dipartimento di Energetica, Via Brecce Bianche, Monte Dago, 60131 Ancona, Italy

ARTICLE INFO

Article history:
Received 9 November 2006
Received in revised form 21 February 2008
Accepted 18 June 2008
Available online 8 August 2008

Keywords:
Adsorption cooling
Solar ice-maker
Climatic data
Ice-maker simulation

ABSTRACT

This paper presents a model for dynamic simulation of an adsorptive ice-maker. The model describes the different phases of the thermodynamic cycle of the ice-maker components: solar collector, adsorbent bed, condenser and cold chamber (evaporator and water to be frozen). The adsorbent/adsorbate working pair is active carbon/methanol.

The simulations were performed for a whole year using measured climatic data of Messina (38°12′N). The detailed results of a week of June and December 2005 are shown, as representative of typical summer and winter conditions. These simulations showed that the ice-maker is able to freeze 5 kg of water during all days of June, and, if the weather conditions are not too unfavourable, also during December. Further simulations, carried out for the whole year 2005, demonstrated that during the most part of the year (from April to October) a daily ice production (DIP) of 5 kg can be obtained, and an equivalent daily ice production (DIP_{eq}) near to 5.5 kg can be reached. During the months of February and March the average monthly DIP is about 4 kg. Finally, for the coldest months (January, November and December) the DIP was 2.0–3.5 kg.

The average monthly solar coefficient of performance (COPs) varies from a minimum of about 0.045 (July) to a maximum of 0.11 (January), with an annual mean of 0.07.

1. Introduction

Adsorptive machines driven by solar energy are cheap, simple and not polluting solutions for cold production in remote areas far from electric grid, but where the solar radiation is widely available [1,2]. The operating principle of such machines is based on the reversible physical adsorption of vapour (e.g. water, methanol) on the surface of a porous solid (e.g. silica gel, activated carbon). An attractive application is the intermittent "adsorptive solar ice-maker", which consists of a small size adsorptive reactor connected or integrated into a solar collector for regeneration of the sorbent material during the day, and to an evaporator for ice production during the night.

Several authors carried out experimental and/or theoretical studies aimed to the development of efficient adsorptive solar adsorption systems.

Among the most interesting experimental works, Sumathy and Z.F. Li 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 the activated carbon/methanol pair [3,4]. From their experiments resulted that this system can produce 4–5 kg ice daily, with a solar COP of 0.10–0.12. These values are in good agreement with those reported by M. Li [5] for a similar flat-plate ice-maker tested in Shanghai: 3.5–4.5 kg of ice and a COP of 0.12–0.147, for a solar collector of 0.75 m^2. Anyanwu and Ezekwe [6] designed, constructed and tested in Nsukka, Nigeria, a flat-type solar adsorption refrigerator using the activated carbon/methanol pair, 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". Hildbrand et al. [7] developed an adsorption refrigerator based on silica gel/water pair; the total solar collector area was 2 m^2. The experiments were carried out over a period of 68 days in Yverdon-les-Bains, Switzerland, and showed the significant influence of the environmental conditions on the system performance. The solar COP was between 0.12 and 0.23.

The prototype designs in [3–6] have been supported by simple mathematical models based on general energy balances and COP calculations. Instead, other models for simulation of the heat and mass transfer processes through the porous adsorbent bed of a solar powered ice-maker, were proposed in [8–12]. In particular, Passos et al. [8] presented a model which accounts for the resistances to mass transfer in the pellets by a linear driving force equation. They calculated the solar collector temperature, the exchanged mass of methanol and validated the model by experimental results. Hu [9] simulated a tubular solar collector to be used in an intermittent non-valve solar powered activated carbon/methanol refrigerator. The calculated temperature and methanol concentration

* Corresponding author. Tel.: +39 90 624243; fax: +39 90 624247.
E-mail address: gaetano.maggio@itae.cnr.it (G. Maggio).

0196-8904/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enconman.2008.06.020

Nomenclature

A_i	heat transfer surface, m^2 (i = 1–5, 9)
a_i, b_i	constants for equilibrium equation of adsorbent/adsorbate (i = 0–3) (see Eqs. (8) and (9))
c	specific heat, J kg^{-1} K^{-1}
c_i	constants for condensation/evaporation pressure (i = 0–3) (see Eqs. (11a) and (11b))
COPs	solar coefficient of performance
d_i	constants for latent heat of condensation/evaporation (i = 0–3) (see Eq. (12))
DIP	daily ice production (kg)
I_β	available solar radiation @ β = 30°, W m^{-2}
K_i	flag: 0 or 1 (i = 1–3) (see Eqs. (2) and (6a and b))
L_a	adsorbate latent heat of condensation/evaporation, J kg^{-1}
L_w	water latent heat of solidification, 334.4 × 10^3 J kg^{-1}
m	mass, kg
m_a	initial adsorbate mass inside the evaporator, kg
m_w	liquid water mass, kg
n	solar collector area, m^2
p	pressure, Pa
R	gas constant for adsorbate, J kg^{-1} K^{-1}
T	temperature, K
t	time, s
t_{cycle}	cycle time, s
U_i	global heat transfer coefficient, W m^{-2} K^{-1} (i = 1–9)
U_α, U_β	global heat transfer coefficient, W m^{-2} K^{-1} (see Table 2)
w	uptake, kg kg^{-1}

Greek letters

$(\tau\alpha)_{eff}$	transmittance/absorptivity coefficient
ΔH	adsorption/desorption enthalpy, J kg^{-1} (see Eq. (10))
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
amb	ambient
c	condenser
eq	equivalent
ev	evaporator
ice	iced water
lw	liquid water
m	solar collector (i.e. metallic housing of the adsorbent material)
s	solid adsorbent material (dry)
w	water
β	tilt angle

Superscripts

C	closed ventilation windows
O	open ventilation windows

maps inside the collector tube, at different times of the day, were presented. Anyanwu et al. [10] modelled the refrigerator prototype presented in [6] to study the influence of various parameters on COP. The parametric study revealed that the solar refrigerator performance strongly depended on the absorptivity of the collector surface coating material. A two-dimensional transient heat and mass transfer mathematical model has been proposed by M. Li and Wang [11] for a flat-plate solar collector of 1.5 m^2, calculating an ice production of 8 kg and COP of 0.125, in agreement with experiments. Day and Sumathy [12] used a model to study a solar adsorbent cooling system in which the adsorber is a metal tube packed with activated carbon/methanol pair and surrounded by a vacuum glass tube. This model, differently from those proposed in [8–11], accounted for the effects of non-uniform pressure distribution.

The works presented in [8–12] were mainly devoted to accurate modelling of the sorbent bed, but are not suitable to satisfactorily describe the other components of the ice-maker system; besides, they have been applied by simulating just one or two days. On the contrary, some models which accounted for the various system components have been proposed in [13–15]. In particular, Leite and Daguenet [13] used a predictive model for a solar adsorption ice-maker, obtaining an average net solar COP of 0.13 and 7–10 kg/day of ice production. Hu and Exell [14] developed a uniform pressure model to simulate the daily performance of a refrigerator with tubular flat-plate collector (1.01 m^2 effective area). The model has been used to evaluate the influence of some design parameters and operating conditions on the system performance. A maximum solar COP of about 0.080 has been calculated. Boubakri et al. used experimental data of two adsorptive flat-plate ice-makers tested in Agadir, Morocco, to study by model [15] the performance sensitivity with respect to various physical parameters of the units. They obtained an average ice production of 5–6 kg m^{-2} for a system based on activated carbon AC-35/methanol pair.

Also these models considered climatic conditions for a short period, with the exception of Leite and Daguenet [13], but they limited their investigation to "the hottest 6 months in João Pessoa, Brazil".

In this paper, a new mathematical model has been developed with the following aims: (a) simulate a whole ice-maker system and calculate the descriptive parameters (e.g. adsorbent, solar collector, condenser and evaporator temperature; adsorbent pressure, methanol uptake, etc.) and performance parameters, as a function of real climatic conditions; (b) evaluate the performance of the ice-maker for a period as long as a whole year. Therefore, this represents an innovative contribution to the current state-of-art, because the proposed model is a useful tool to accurately simulate the operation of all ice-maker components and determine the system performance – in terms of COPs, DIP and DIP$_{eq}$ – for a whole year of continuous operation. Such features have not been reported in previous works.

The model is based on energy balances for the adsorbent reactor and the connected heat exchangers. The climatic data used as input parameters were experimentally recorded by means of a meteo-station installed at the CNR-TAE Institute in Messina. Values of solar radiation and ambient temperature taken every 10 min for the whole year 2005, were used to perform the simulations.

2. Operating principle

An adsorptive solar ice-maker is made of the following components: a solar collector, in which the adsorbent material (active carbon) is embedded; a condenser for the adsorbate (methanol)