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Experimental chiller with silica gel: Adsorption kinetics analysis and performance evaluation

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ABSTRACT

Adsorption technology is a promising, low carbon intensity option for air conditioning and refrigeration. Adsorption kinetics is a key performance factor for such systems. This paper presents an adsorption kinetics and performance assessment of an experimental adsorption chiller with silica gel and water as working pair. The adsorbent bed heat exchanger is equipped with silica gel in loose grains fitted between finned tubes. Pressure, temperature and adsorbate flow measurements along the thermodynamic cycle are performed for two different options of adsorbent particle fraction sizes to compare the resulting dynamics and performance. *COP* is 0.53 and *SCP* is 68 $\mathrm{W \cdot kg^{-1}}$ for 2.0 mm dia. silica gel and a 80/30/15 °C triplet. COP is 4 % worse when 0.26 mm silica gel is used, due to the lower porosity and lower thermal conductivity presented by the crushed adsorbent. A mass diffusion algorithm is considered in the numerical model. Good agreement between experimental and calculated data has been reached. The maximum temperature level needed for desorption in the 70–80 °C range is compatible with the use of water heated by flat-type solar collectors, and low-grade waste heat from industrial processes.

1. Introduction

In a recent UNEP report [1], air conditioning is recognized as a vital means for sustainability, due to its importance to meet fundamental human needs, whereas some negative environmental impacts, especially related with materials, direct and indirect greenhouse gas (GHG) emissions, are pointed out. These impacts are mostly associated to the choice of refrigerants, both direct — due to chemical composition — and indirect — such as use of energy and materials; to the emission of GHG along life cycle. Recent climate negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) led to the Paris Agreement, in which the 197 Parties express the aim to reach global peaking of GHG emissions as soon as possible, and to undertake rapid reductions thereafter, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks in the second half of this century [2]. This balance means that global net GHG emissions should fall to zero by 2100, in order to avoid the most catastrophic consequences of anthropogenic climate change.

Air conditioning driven by solar energy emerges as an interesting option to address the sustainability challenge, due to the use of a free, renewable energy source, leading to a lower carbon intensity if compared with electric systems. Adsorption solar air conditioning systems bring additional positive factors:

1. Refrigerant fluids obtained from renewable sources, such as water, ethanol, and methanol, are suitable to adsorption machines; and
2. Working pairs such as silica gel-water result in maximal performance at temperature levels that do not require concentration of solar radiation, leading to simple designs.

Moreover, such systems do not use major moving parts such as compressors, etc., therefore its reliability is favoured, and the noise level is very low.

The attractiveness of adsorption solar air conditioning has become increasingly prominent by:

1. The fact that these systems do not need fluorinated refrigerant options, restricted by existing and proposed new regulation due to impacts of HFC, HCFC, and CFC on climate and, in case of chlorinated compounds, also on the stratospheric ozone layer;
2. The growing interest on equipment specifically designed for high ambient temperatures;

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Nomenclature

A	surface area (m^2)
a,b,c	coefficients (–)
C_p	specific heat at constant P ($kJ \cdot kg^{-1} \cdot K^{-1}$)
COP	coefficient of performance (–)
D	diffusivity ($m^2 \cdot s^{-1}$)
h	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
i	specific enthalpy ($kJ \cdot kg^{-1}$)
K	constant (–)
K_p	permeability (m^2)
m	mass (kg)
$\dot{m}_a$	working fluid massic flow rate ($kg \cdot s^{-1}$)
n	homogeneity parameter (–)
P	pressure (Pa)
Q	heat (J)
$\dot{Q}_{eV}$	cooling power (W)
r	radius of the adsorbent particle (m)
SCP	specific cooling power ($W \cdot kg^{-1}$)
T	temperature (K)
t	time (s)

Greek symbols

Δ	difference (–)
ε	porosity (–)
φ	surface contact fraction (–)
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
λ_g^*	apparent conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
λ_R	radiation conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
λ_{so}	conductivity particle-gas ($W \cdot m^{-1} \cdot K^{-1}$)
ρ	density ($kg \cdot m^{-3}$)
χ	adsorbate uptake ($kg \cdot kg^{-1}$)
ω_0	maximum adsorption volume ($m^3 \cdot kg^{-1}$)

Subscripts

a	adsorbate
ads	adsorbent
ap	apparent
des	desorption
ef	effective
eV	evaporation
f	fluid
g	gas
t	heat exchanger tube
s	saturation
sor	sorption
1	initial state

3. Legal requirements limiting emissions of chemicals; and
4. Consumer demand for decentralized energy generation, motivated by energy price and availability fluctuations in certain regions.

On the other hand, an adsorption chiller is heavy and bulky if compared to vapour compressor equipment with a similar capacity, thus requiring more materials and room space. It has been pointed out that the major problem with this technology is related to its low cooling power density [3], taking into account heat and mass transfer limits in the solid adsorbent bed, along the cycle formed by adsorption and desorption processes. The investigation of the behaviour of adsorbent beds containing adsorbents in loose grains from an adsorption kinetics standpoint has been focused by many studies, aiming to achieve higher sorption rates, more compact and efficient configurations.

Many developments take into account mass transfer by diffusion inside the adsorbent particles, e.g. Solmus et al. [4] and Hong et al. [5]. However, the degree of influence of the intraparticle diffusion is in general not presented in literature.

Relevant contributions on chiller performances with the silica gel-water pair were reported for instance by Chang et al. [6], who obtained a COP of 0.45 with a single adsorber, under standard test conditions. Xia et al. [7] developed a two-adsorber unit, obtaining a maximum COP of 0.43 at a 84.4/30.5/16.5 °C triplet, while Gong et al. [8] reached an optimal COP of 0.43 with hybrid LiCl in silica gel adsorbent, mass recovery, and evaporators equipped with heat pipe, under 90/30/20 °C temperature set. Lu et al. [9] obtained a similar COP level of 0.42 at a 86/32/15 °C condition. Niazmand et al. [10] developed a 3-D numerical model by which, considering a fin height range of 3–12 mm, a maximum COP was obtained with 12 mm fin height, whereas a maximum SCP would be experienced with the smallest fin height considered. Wang et al. [11] conducted a performance simulation of silica gel-water multi-bed chillers with good agreement with experimental data. Hong et al. [12] performed a parametric study of a plate-type adsorber heat exchanger with embossed fins and composite $CaCl_2$ in mesoporous silica gel-water pair, with an optimal COP of 0.512. Pan et al. [13] obtained COP of 0.51 at 86/30/11 °C with a 42.8 kW chiller with modular adsorbers.

This article describes the development of an experimental, single-adsorber adsorption chiller using silica gel-water as working pair, chosen because of its non-toxic, low environmental impact characteristics, good thermodynamic properties, and because the raw materials are especially abundant in nature. The experimental results are compared with those obtained by a mathematical model, which has been developed to understand the influence of the various physical phenomena on chiller performance. Further experimental developments will benefit from findings of this study such as the following:

1. The optimized adsorbent grain size for both COP and SCP lays on a single upper limit of an region in which performance is insensitive to size, and it is intermediate to the ones initially used;
2. A flat-type solar collector can be considered, since the best hot source temperature for COP is in its operational temperature range;
3. Better temperature uniformity along the adsorbent bed is obtainable by a convenient reduction of its current length.

2. Experimental chiller setup and procedure

The working principle of an adsorption machine is based on the difference in adsorption capacity of a solid adsorbent with temperature and pressure. The refrigerant flows through the circuit components as it is submitted to different pressures by temperature variations. The adsorber serves as a high temperature heat source to the refrigerant fluid when it is desorbed from the adsorbent bed, and as an intermediate temperature heat sink during the evaporation of the refrigerant fluid at low temperature in the evaporator.

The experimental setup follows the circuit configuration shown in Fig. 1. It is composed by one finned tube adsorber containing of silica gel in loose grains, a water-cooled condenser, an evaporator with a small built-in circulating pump, and a double suction line.