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On the impact of different management strategies on the performance of a two-bed activated carbon/ethanol refrigerator: An experimental study

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ABSTRACT

In the present work, an experimental study on a lab-scale adsorption refrigerator, based on activated carbon/ethanol working pair is reported. An extensive testing campaign has been carried out at the CNR ITAE laboratory, with multiple aims. First, the performance has been evaluated in terms of both COP and Specific Cooling Power (SCP), under different boundary conditions, including both air conditioning and refrigeration applications. Attractive SCPs, up to 180 W/kg and 70 W/kg for air conditioning and refrigeration, respectively, were measured. Under the same conditions, COP between 0.17 and 0.08 were obtained. In addition, different management strategies, namely, heat recovery between adsorbers and re-allocation of phase durations, were evaluated to identify their influence on the system. Both strategies confirmed the possibility of increasing COP and SCP up to 40% and 25%, respectively. Moreover, a design analysis based on the experimental results has been carried out, to suggest possible improvements of the system. The obtained results demonstrated the possibility of employing a non-toxic refrigerant like ethanol reaching performance comparable with other harmful refrigerants like ammonia and methanol.

1. Introduction

Energy efficiency and energy savings are critical issues for most applications today, ranging from residential to industrial and transportation fields. Among them, refrigeration accounts to GHG emissions up to 1000 kton/y of CO_2 equivalent [1], 25% of which because of air conditioning and refrigeration needs in the transportation sector [2] and 40% in the commercial sector [1]. Currently, refrigeration demand is mainly covered using vapor compression systems employing R404a, with a GWP of 3922 [3]. To mitigate such a situation, and comply with the international standards on energy efficiency, thermally driven systems represent a viable and promising alternative, since they can be run by waste and renewable heat coming from, for instance, Internal Combustion Engines [4], solar thermal collectors [4] or micro-cogeneration units (mCHPs) [5], to produce refrigeration energy.

In such a context, adsorption systems represent a promising choice since they can be operated by low/medium temperatures (i.e. <100 °C), do not suffer of shock and vibrations-related problems and employ zero GWP refrigerants like water, alcohols and ammonia [4].

In particular, adsorption refrigeration feasibility and employment has been exploited for several years, regarding both the study of working pairs [6] and prototypal activity [4]. Most of the works available in literature have been focused on ice makers for production of ice flakes to be employed on board of fishing vessels or for coupling with solar collectors, with the adsorbent embedded into the collector [7] and regenerated with a night-day cycle.

Only few reports exist on adsorption systems able to deliver a continuous cooling effect, which are generally based on methanol or ammonia as working fluid. Wang et al. [8] presented an activated carbon–methanol adsorption refrigerator comparing an adsorber with granular or solidified carbon. Consolidated adsorber showed higher performance, with maximum values of SCP (Specific Cooling Power) of 35 W/kg. Again Wang et al. [9] reported the activity carried out on different adsorber configurations, with activated carbon in either consolidated or granular configuration with methanol as refrigerant. Experiments conducted with regeneration temperature of 110 °C and cooling with tap water, producing refrigeration at −7 °C, demonstrated that the consolidated adsorber showed slight better performance than the granular one, with SCP of 16 W/kg and COP of 0.125. Lu et al. [10] presented a heat pipe adsorption refrigerator, in which activated carbon-$CaCl_2$ is used as compound adsorbent and ammonia as refrigerant. Experiments were conducted with desorption temperatures

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Nomenclature

Symbols

cp	specific heat [kJ/(kg K)]
m	mass [kg]
$\dot{m}$	flow rate [kg/s]
psat	saturation pressure [kPa]
T	temperature [°C]
R	adsorption/desorption ratio [–]
V	volume [m^3]
w	uptake [g/g]
τ, t	time [s]

Subscripts

adsorbent	adsorbent
adsorber	adsorber
adsorption	adsorption phase
cond	condenser
cycle	cycle
des-bed	desorber
desorption	desorption phase
eV	evaporator
in	inlet
out	outlet

Abbreviations

COP	coefficient of performance
LT	low temperature
MT	mean temperature
HT	high temperature
SCP	specific cooling power [W/kg]
VSCP	volumetric specific cooling power [W/dm^3]

ranging from 110 °C to 130 °C and evaporation temperatures of −15 °C and −20 °C. Average SCP and COP measured were 161.2 W/kg and 0.12. In [11], Lu et al. presents the results of a heat pipe adsorption refrigerator employing $CaCl_2$ and activated carbon–ammonia as working pair and used for both ice production and near-zero degrees cold water production. SCP and COP measured were up to 300 W/kg and 0.20. Tamainot-Telto and Critoph [12] realized a prototype, employing a monolithic carbon-ammonia pair, for continuous refrigeration production. The performed tests at regeneration temperature around 100 °C, cooling at 20 °C and refrigeration at −8 °C allowed to obtain 50 W/kg and 0.09 of specific refrigeration power and COP respectively. Pan et al. [13] developed and tested an ammonia-based refrigerator, employing composite activated carbon/$CaCl_2$ as adsorbent and a mass recovery strategy. The prototype was efficiently regenerated employing heating source at 130 °C, producing 210 W/kg with a COP of 0.19 when cooled at 25 °C, delivering refrigeration power at −5 °C.

Despite the interesting performance of such systems, both methanol and ammonia present some critical issues that might limit their applications, especially in food processing: they are corrosive, therefore requiring special construction materials [14], and toxic, making any refrigerant loss dangerous in case of food storage. Hence, another refrigerant that could be considered for application in adsorption refrigerators, especially for its non-toxicity, is ethanol.

El-Sharkawy et al. in [15] experimentally studied ethanol adsorption onto activated carbons, by measuring the adsorption properties of a Maxsorb III-ethanol through TGA analysis, showing that the proposed material can adsorb up to 1.2 kg of ethanol per kg of adsorbent. Moreover, the authors have provided a thermodynamic model, calculating a specific cooling effect of 420 kJ/kg for a cycle with regeneration temperature of 80 °C and 30 °C and 7 °C as condensation and evaporation temperatures respectively. El-Sharkawy et al. [16] have experimentally and numerically studied also the adsorption equilibrium of activated carbon-fibres for ethanol adsorption. In the relative pressure range of 0.2–0.5, which is the useful range for the application in adsorption refrigerators, an adsorption capacity of 0.5–0.65 kg of ethanol per kg of adsorbent have been measured. More recently, Brancato et al. [17] have measured the ethanol adsorption capacity of different commercial carbonaceous materials, produced from different bases (coal, coconut shell) and having different morphology (grains, pellets, fibres). Among them, commercial grains of the SRD 1352/3 type have revealed an adsorption capacity up to 0.56 kg of ethanol per kg of adsorbent, thus proving the interesting features for the application in sorption chillers.

Analytical models to assess the performance achievable with activated carbon/ethanol systems have been proposed as well: Saha et al. [18] have modelled a 2-beds adsorption chillers employing activated carbon fibres/ethanol as working pair under the boundary conditions of 65–85 °C as heat source, 30 °C as condensation temperature and 10–14 °C as evaporation temperature. The ethanol system was compared to a silica gel/water one, showing that, for low temperature heat sources, the achievable COP of ethanol is higher of that of the silica gel system, with a cooling capacity only about 10% lower. In [17], a thermodynamic model for the calculation of COP achievable for different activated carbon/ethanol working pairs is described, with the best materials presenting theoretical COP of 0.55 for a refrigeration cycle.

In [19], an experimental activity for the optimization of adsorbers employing ethanol as refrigerant is presented. Dynamics of adsorption is studied by means of a gravimetric version of the Large Temperature Jump approach, known as G-LTJ apparatus, in different heat exchangers with realistic configurations. For a refrigeration cycle with 90 °C heat source, 25 °C condensation and −3 °C evaporation temperatures, a volumetric cooling power of 0.5 kW/dm^3 was estimated, which evidenced the promising potential of such working pair in a full-scale system.

One of the challenges that need to be assessed when applying sorption technology is the low efficiency of the system, especially if compared to traditional systems. In order to mitigate such issue, despite the improvement of the adsorbers and the research on materials, optimization in terms of cycle management has been proposed. An overview of the cycle managements studied during the last decades is given in [20]. Two major types of advanced cycles can be identified, based on thermodynamic and dynamic optimization. Among the former ones, the most studied and applied is the heat recovery cycle, consisting in the transfer of partial adsorption heat and sensible heat from the adsorber undergoing pre-cooling to the one which is being preheated [21]. Such a strategy has been experimentally proven to reduce heat demand for the operation of the system: for the activated carbon-methanol prototype described in [21], an increment of COP up to 25% was measured. Similarly, mass recovery cycle, firstly proposed by Pons and Poyelle [22], and based on the equalization of pressures among the two adsorbers by the direct connection during isosteric phases, has also been widely employed and proved to be effective in increasing the COP of adsorption chillers and refrigerators, even though extra vacuum components are needed. For