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Design, realization and testing of an adsorption refrigerator based on activated carbon/ethanol working pair

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HIGHLIGHTS

- Development of a lab-scale adsorption refrigerator.
- Optimization of working pair and adsorber configuration through experimental activity.
- Experimental testing of the prototype under real working boundary conditions.

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ABSTRACT

In the present paper design, realization and testing of a novel small scale adsorption refrigerator prototype based on activated carbon/ethanol working pair is described. Firstly, experimental activity has been carried out for identification of the best performing activated carbon available on the market, through the evaluation of the achievable thermodynamic performance both under air conditioning and refrigeration conditions. Once identified the best performing activated carbon, the design of the adsorber was developed by experimental dynamic performance analysis, carried out by means of the Gravimetric-Large Temperature Jump (G-LTJ) apparatus available at CNR ITAE lab. Finally, the whole 0.5 kW refrigerator prototype was designed and built. First experimental results both under reference air conditioning and refrigeration cycles have been reported, to check the achievable performance. High Specific Cooling Powers (SCPs), 95 W/kg and 50 W/kg, for air conditioning and refrigeration respectively, were obtained, while the COP ranged between 0.09 and 0.11, thus showing an improvement of the current state of the art.

1. Introduction

Adsorption heat transformers (AHTs) comprise different technologies, which exploit thermal energy as driving source, to produce either heating, cooling or refrigeration effect [1,2]. These technologies have been widely studied, especially during the last decades, mainly for air conditioning and heat pumping purposes, in order to reduce electrical energy consumption and ozone depletion caused by the vast diffusion of vapor compression machines [3,4]. Such an intensive research activity has made both adsorption heat pumps and chillers ready for the commercialization of the first products [5,6]. Nevertheless, as pointed out in several studies [7,8], also refrigeration can be considered as a high-impact technology, both in terms of primary energy consumption and harmful emissions. Indeed, refrigeration process is widely employed in several sectors (e.g. domestic, industrial and transports) since it is often associated to food processing, storage and transport. Despite the centrality of this process in so different fields of application, refrigeration based on adsorption technology is still limited to few examples and not enough developed to be considered suitable for commercialization. Instead, the possibility to couple adsorption systems with a wide variety of thermal sources, ranging from solar collectors to waste heat and mCHP units, makes it a promising technology for better energy utilization [2,9].

Looking through the literature, several studies dealing with the development and optimization of adsorption refrigerators starting from the theoretical modeling, up to working pairs selection and small scale prototypes design and realization are available [9–

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Nomenclature

T	temperature (°C)
m	mass (kg)
h	enthalpy (kJ/kg)
COP	coefficient of performance (–)
SCP	specific cooling power (W/kg)
cp	specific heat (kJ/(kg K))
HT	high temperature (°C)
LT	low temperature (°C)
MT	medium temperature (°C)
Q	energy (kJ)
u	uncertainty (%)
$\dot{m}$	mass flow rate (kg/s)
$\dot{V}$	volume flow rate (LPM)
V_{ads}	volume of adsorbers (m^3)

Greek symbols

τ	time (s)

Subscripts

ads	adsorption
des	desorption
eV	evaporator
evap	evaporation
in	inlet
ish	isosteric heating
bed	adsorbent bed

11]. The majority of these studies is focused on the solar adsorption refrigeration based on day-night cycle. In such a configuration, the adsorber consists of the adsorbent material in direct contact with the solar collector, in order to be regenerated during daytime with solar radiation, while after the sunset, it is connected to the evaporator in order to produce cooling effect in a cold box. The produced refrigeration energy is usually stored by means of freezing water, which allows preserving the maintenance of the perishable stuff (e.g. food, vaccine) during the subsequent day [12].

Few papers report activities on adsorption refrigeration prototypes able to produce quasi-constant refrigerating power. The developed prototypes employ either activated carbon or sorbent composite as adsorbent material and either ammonia or methanol as refrigerant. Wang et al. [13] reported the activity carried out on different adsorber configurations, with activated carbon either in consolidated or granular way and 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. Telto and Critoph [14] 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. Lu and Wang [15] reported experimental testing of an adsorption refrigerator employing an adsorbent composite silica gel/LiCl and methanol as working pair, implementing mass recovery strategy. The prototype achieved 51 W/kg with a COP of 0.13 when regenerated at about 90 °C and cooled at 25 °C, to produce refrigeration power at −4 °C. Pan et al. [16] 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 their good thermo-physical properties, in particular the high latent heat of vaporization, both methanol and ammonia still present some limits for their applications: both the refrigerants are toxic, and, additionally, ammonia-based systems need temperature above 100 °C to reach optimized performance [17]. Finally, they are corrosive, which makes impossible to employ copper and aluminum as constructing materials. Furthermore, the sorbent composites, whose thermodynamic performance are really promising for adsorption refrigeration applications, still suffer of some possible limitations. Indeed, their long-term cycling stability has never been carefully investigated, which can cause massive corrosion in case of leakage of salts from host matrix. Furthermore, due to the chemical reaction occurring between adsorbate and salt, usually higher regeneration temperature are necessary and the adsorption/desorption kinetic is slowed down if compared to physical adsorbents [18].

Another refrigerant widely studied for such a kind of application is ethanol. Despite its lower evaporation enthalpy, compared to methanol and ammonia, it is considered as a promising alternative refrigerant, thanks to its good chemical stability and non-toxic behavior. Accordingly, several studies are reported in the literature, dealing with activated carbon/ethanol working pair characterization both from thermodynamic and dynamic point of view [19,20]. They confirmed that also ethanol can be satisfactorily employed, especially if proper attention is paid towards the optimization of the adsorber. Nevertheless, no scale up to prototype level has been reported so far to verify its performance closer to real application. This represents an important lack of knowledge in the development of adsorption refrigeration technology, since, in order to highlight its main strength and weakness, it is necessary to experimentally analyze achievable performance on a representative scale, close to the real one.

In such a background, the present work will illustrates the design, realization and testing of the first lab scale adsorption prototype reported in literature employing activated carbon/ethanol as working pair for continuous refrigerating power production. In order to properly design the prototype, preliminary activities for the selection of the best performing activated carbon on thermodynamic basis have been performed. Moreover, the adsorber design (i.e. integration of activated carbon inside an efficient heat exchanger) has been optimized through experimental kinetic characterization of different configurations. Finally, the full scale adsorption refrigerator prototype, with a nominal refrigeration power of 0.5 kW, has been designed and realized. First experimental results under controlled working boundary conditions are then provided. This activity will prove the feasibility of employing the investigated working pair as well as the optimized adsorber configurations under real operating conditions of a lab-scale adsorption refrigerator.

2. Prototype design

The whole design of the prototype was carried out following different steps of development. First of all, a thermodynamic analysis of the most promising activated carbons on the market for