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A new management strategy based on the reallocation of ads-/desorption times: Experimental operation of a full-scale 3 beds adsorption chiller

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HIGHLIGHTS

- An innovative 3-beds adsorption chiller is presented.
- Innovations proposed are the hybrid coated/granular adsorbers and the management strategy.
- The management is based on the reallocation of the ads-/desorption durations.
- A wide experimental characterization was carried out.
- Volumetric cooling power up to 275 $kW/m^3_{adsorber}$ was measured.

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ABSTRACT

In this paper, a wide experimental characterization campaign aimed at measuring the performance of an innovative 3-beds adsorptive chiller prototype is reported.

The prototype was designed to employ a new management strategy, based on different durations of adsorption and desorption isobaric steps of a basic temperature driven adsorptive cooling cycle and aimed at achieving high cooling power density.

The performance were measured, in terms of Average Cooling Power (ACP), cooling COP and Volumetric Cooling Power (VCP), using a test bench suitable for the characterization of thermally driven cooling/heating machines, under typical boundary conditions of air conditioning applications. A sensitive analysis was carried out to assess the effect of several parameters (e.g. the temperature lift $T_M - T_L$, driving temperature T_H and cycle time). on the operation of the chiller. The results of the experimental activity depict a complete performance map for the tested chiller and demonstrate the potential of the new cycle management strategy.

At nominal boundary conditions (i.e. $T_H \sim 90$ °C, $T_L \sim 18$ °C and $T_M \sim 25$ °C), the cooling machine was able to deliver an ACP of 4.4 kW and an overall VCP of 9.4 kW/m^3, with a COP of 0.35 while the VCP referred to the volume of the only adsorber was $\sim$275 kW/m^3.

1. Introduction

Utilization of energy from renewable sources and the reutilization of waste thermal energy have gained major interest during the last years, with the goal of reducing both the share of traditional fossil energy sources consumption and the energy-related environment pollution. Indeed, growing concerns towards the environment are testified by international interest in containing the high GWP/ODP emissions and the consequent climate changes [1].

The influence of HVAC systems on the atmospheric pollution has already been proved to be relevant [2,3]. Possible strategies for the reduction of the emission of polluting gases due to heating and cooling sectors are the substitution of the currently employed refrigerants, characterized by high GWP and ODP [4] as well as the application of alternative technologies, such as HVAC systems driven by thermal energy (e.g. solar heat or waste heat), instead of traditional vapour compression ones driven by electricity.

Among the innovative environmentally friendly cooling technologies, adsorption machines for air conditioning and refrigeration represent a viable and promising technology, since they can be driven by low-grade heat sources and employ clean refrigerants (e.g. water, ethanol) [5,6].

Nonetheless, still opened critical issues, mainly represented by high capital cost and low COP and power density, limit the large scale

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Nomenclature

Symbols

ACP	average cooling power (W)
AdHEX	adsorbent heat exchanger
COP	coefficient of performance (–)
c_p	specific heat [kJ/(kg K)]
GHG	greenhouse gas
h	convective heat transfer coefficient [W/m^2 K]
H	enthalpy [J/kg]
HEX	heat exchanger
HTF	heat transfer fluid
HVAC	heating, ventilation and air conditioning
m	mass, sorbent dry mass [kg]
$\dot{m}$	flow rate [kg/s]
λ	thermal conductivity [W/m K]
ODP	ozone depletion potential
Q	thermal energy (J)
R	adsorption/desorption duration ratio (s/s)
s	thickness [m]
S	heat transfer surface of HEx [m^2]
τ	time (s, min)
T	temperature (°C)
u	uncertainty (–)
$\dot{V}$	volumetric flow rate of heat transfer fluid (LPM)
V	volume (m^3)
VCP	volumetric cooling power (W/m^3)

Subscripts

AdHEx	adsorbent heat exchanger
Al	aluminum
Amb	ambient
des	desorption
ev	evaporation
in	inlet
ins	insulating material
H	high
L	low
M	medium
Opt	optimum
Out	outlet
Ref	refrigerant
Sens	sensible
Ss	stainless steel

diffusion of such systems. In Table 1, some of the most recent adsorption chiller prototypes/commercial machines and developed adsorber concepts are listed and their main performance indicators are reported. Where possible, a distinction has been made between the volumetric cooling power calculated with respect to the overall volume of the chiller ($VCP_{chiller}$) and the one calculated considering only the volume of the adsorber (VCP_{AdHex}).

All the prototypes and commercial systems shown in Table 1 employ the classical double-bed architecture with the adsorbers operating in counter-phase by a standard management strategy based on equal duration of adsorption and desorption steps. The prototypes presented in [7,9] have low $VCP_{chiller}$ (up to 3 kW/m^3), while the commercial systems [10,11] and the prototype developed for automotive applications presented in [8] have $VCP_{chiller}$ exceeding 12 kW/m^3. This is due to the optimised design of all the components of these systems to fit specific dimension requirements.

Taking into account only the volume of the adsorber, the VCP is below 100 kW/m^3 for all the listed full scale machines while for the lab scale adsorber concepts [13–15], only the direct synthesis of the adsorbent material on the HEx assures high value of power density (up to 320 kW/m^3).

Numerical studies of more complex machine configurations were discussed in [16,17] demonstrating the potentiality of such kind of machine layouts. To improve the dynamic performance of the adsorptive technology and consequently the cooling power density, the research efforts are mainly addressed towards an increase of the efficiency of the main components (i.e. adsorber and evaporator/condenser) at different levels:

(i) at the adsorbent material level, the research focuses on the development of new materials or adsorbent configurations [13–20] as well as the proper selection/tailoring of the optimum adsorbent for the specific application and/or boundary conditions,

(ii) at components level, the development of efficient evaporator/condenser is the key issue: especially when water is used as refrigerant, the low heat transfer coefficients and the still partial knowledge of the phase change phenomena limit the proper design of these components [21,22],

(iii) finally, optimization of the coupled system (adsorbent material plus heat exchanger) is mandatory to get high VCP [23–25].

A different approach to improve the dynamic performance of an adsorption machine has been recently proposed in [26] and further investigated in [27] by testing small scale adsorbers through a dedicated test bench. This approach aims at getting high power density by a proper reallocation of the ratio between the adsorption and desorption steps duration according to the nature of the working pair and the operating conditions. Results reported in [26,27] showed that, on the basis of the boundary conditions, adsorption and desorption can have different sorption kinetics and that a proper management strategy optimization allows a remarkable increasing in overall performance.

On the basis of the previously mentioned results, the authors developed a full scale adsorption chiller prototype based on an innovative “3 hybrid -adsorbers architecture” able to operate with an adsorption-

Table 1
Analysis of different adsorption air-conditioning prototypes and commercial machines.

Reference	Working pair	No. adsorbers	Cooling capacity	COP	$VCP_{chiller}$	VCP_{AdHex}
[7]	Silica gel/Water	2	5.7 kW	0.4	3.06 kW/m^3	
[8]	AQSOA FAM Z02 (loose grains)/Water	2	2.3 kW	0.3	13.50 kW/m^3	92 kW/m^3
[9]	LiCl-Silica gel/methanol	2	4.9 kW	0.4	2.65 kW/m^3	
[10]	Silica gel/water	2	14 kW	0.6	12.3 kW/m^3	
[11]	Silica gel/water	2	16 kW	0.6	15.4 kW/m^3	
[12]	Silica gel/water	2	15 kW	0.5		20.6 kW/m^3
[13]	SAPO 34 (coating by direct synthesis)/Water	1	–	0.6	–	150 kW/m^3
[14]	SAPO 34 (coating by dip coating)/Water	1	1 kW	0.24	–	93 kW/m^3
[15]	SAPO 34 (coating by direct synthesis)/Water	1	5.6 kW	0.4	–	320 kW/m^3