Adsorption chilling driven by low temperature heat: New adsorbent and cycle optimization

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ABSTRACT

This paper aims to present a new composite sorbent, specifically developed at BIC-RAS to operate at low regeneration temperature ($<70\,°C$), and its testing by a lab-scale adsorption chiller installed at ITAE-CNR. Adsorption equilibrium measurements demonstrated that the new composite, $LiNO_3$/vermiculite, named SWS-9V, exchanges app. 0.4 g H_2O/g in an exceptionally narrow temperature range, 33–36 °C (adsorption at 12.6 mbar) and 62–65 °C (desorption at 56.2 mbar), corresponding to a remarkable heat storage capacity (0.9 MJ/kg). The new sorbent, embedded into an adsorber, was tested at ITAE with the aim to optimize the cycle taking into account both the thermodynamic and kinetic properties of SWS-9V. The results demonstrated that the optimal cycle performance, for given operating conditions, are strongly dependent on the cycle time (τ) and the relative duration (R) of the isobaric adsorption and desorption steps. Indeed, at $T_c = 35\,°C$, $T_e = 10\,°C$ and high driving temperature ($T_d = 90\,°C$), the system provided the best performance at $\tau = 20$ min delivering about 230 W/kg of specific cooling power (SCP) with a coefficient of performance (COP) equal to 0.66 when the adsorption duration is 7 times longer than the desorption one ($R = 7$). Differently, at low driving temperature ($T_d = 68\,°C$), the best performance (COP = 0.59 and SCP = 96 W/kg) were obtained at $\tau = 30$ min, protracting the duration of the desorption step at the expenses of the adsorption one ($R = 0.75$).

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1. Introduction

As response to the ozone-depletion and global-warming effects caused by Chlorofluorocarbons, Hydro-chlorofluorocarbons and carbon oxides emissions, in the last decades considerable efforts were made to develop new cooling and heating technologies. In this context, thermally driven adsorption systems have attracted much attention due to their ability to use environmentally friendly refrigerants and low grade energy from waste heat sources. In addition to these features, other relevant advantages are: the absence of moving parts, simple control and low operation costs. Nevertheless, the widespread market diffusion of adsorption cooling systems still requires the increase in their performance to compete with electric compression machines while the lowering in the thermal level of the driving source is a key issue to win the challenge with other thermally operated cooling technologies.

The current state of art of the adsorption cooling systems is reported elsewhere [1,2]. Currently, R&D activities aim to develop performing adsorbents [3–6], components [7–9] and systems [10–12].The modern strategy of developing materials for adsorption cooling (AC) is a harmonization of the adsorbent with the thermodynamic cycle [3,13,14]. It is traditionally reached by screening of known adsorbents to select the best one for a given cycle [15,16]. An alternative way is tailoring of a novel adsorbent adapted to right this cycle [3,15]. In particular, adsorbents with low regeneration temperature (65–70 °C) are of high current demand as these allow utilization of huge amount of low potential heat that nowadays is irretrievably wasted. One of such adsorbents is presented and studied in this communication. Furthermore, recent studies demonstrated the possibility to fit the management strategy of an adsorption chiller with the kinetic properties of the employed adsorbent material getting a strong increase in the overall performance of such kind of cooling systems. In particular, it was demonstrated that adsorption and desorption phases of the AC cycle, as a rule, require different times due to the difference in kinetics of vapor ads-/desorption observed for many solid sorbents [14,17]. An intermittent AC cycle with variable ads-/desorption duration at fixed total cycle time was investigated in [18]. It was demonstrated that the duration of desorption phase is a very efficient parameter for optimizing the cycle COP and SCP, which can be

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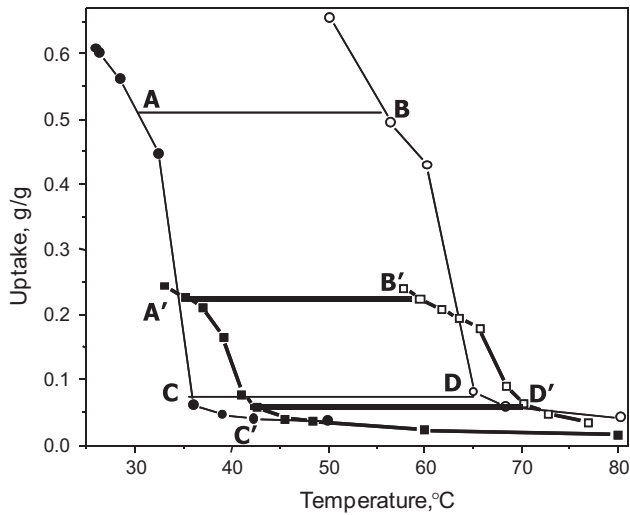E-mail address: alessio.sapienza@itae.cnr.it (A. Sapienza).

Fig. 1. Equilibrium isobars of water adsorption at 12.6 mbar (solid symbols) and desorption at 56.2 mbar (empty symbols) and appropriate AC cycle for the composites SWS-9V (A-B-C-D) and SWS-9L (A′-B′-C′-D).

significantly improved as compared with the common case of equal durations of the AC isobaric phases.

Agreed with above, first we describe the novel composite sorbent of water which was intently synthesized for AC cycles driven by low temperature heat. We measured its isobars of ad- and desorption, plotted and analyzed appropriate AC cycle. At the next stage, we implemented this cycle by means of a single stage lab-scale adsorption chiller and focus our effort on the cycle optimization in terms of cycle time and relative duration of isobaric phases

$(R = <\text{adsorption time}>/<\text{desorption time}>)$ both at low and high driving temperature (T_d).

2. Synthesis and characterization of the new composite sorbent

The new composite sorbent "LiNO$_3$/vermiculite" (SWS-9V) has been specifically developed at BIC-RAS. According to the nano-tailoring approach [3], an adsorbent optimal for AC cycles should have a step-like sorption isobar with the step position T_s close to the minimal desorption temperature T_{min} of a particular cycle. For common air conditioning applications, the desired evaporation temperature T_e equals 7–12 °C and the heat rejection temperature T_c may be fixed at 35 °C. The thermodynamically minimal desorption temperature can be estimated from the universal equation $T_c^2 = T_e \cdot T_{min}$ [13,14] that gives $T_{min} = (60-65)$ °C. In actual practice, the temperature of sorbent dehydration T_s and of the driving temperature T_d have to obey the relation $T_{min} < T_s < T_d$ to ensure sufficient driving force for heat and mass transfer in the adsorber, condenser and evaporator. Taking into account these considerations, it is reasonable to focus on synthesis of a new adsorbent that can be regenerated at 65–70 °C, that has steep isobars of water ads-/desorption and that exchanges large mass of water under the discussed boundary temperatures. These regeneration conditions ($T_c = 35$ °C, $T_s = 65-70$ °C) correspond to the adsorption potential $\Delta F = (4.19-4.88)$ kJ/mol.

Lithium nitrate is a salt which bounds water less strongly than calcium chloride, lithium bromide or calcium nitrate already reported for AC applications [19–21]. Composite LiNO$_3$/silica KSK (SWS-9L) has been tested in a single bed adsorption chiller [18]. This adsorbent was found to be regenerated at quite low temperature of 60–70 °C, and the amount of water exchanged at the
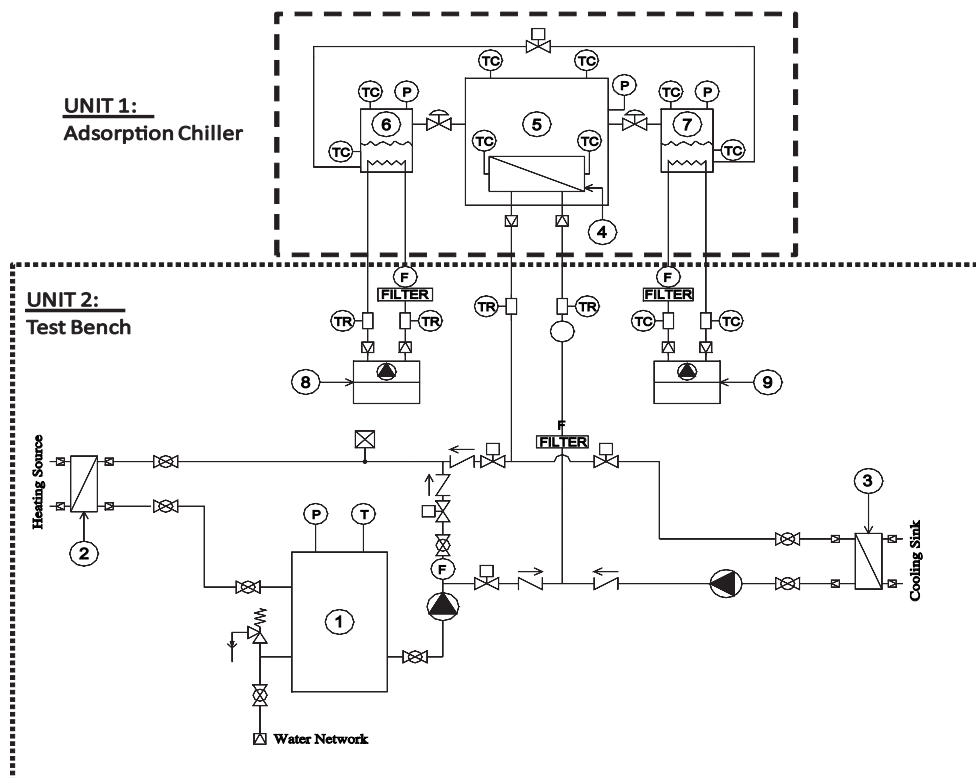

Fig. 2. Scheme of the testing system (the lab-scale adsorption chiller connected to the test bench):1 – heat storage tank, 2 – heat exchanger (heating loop), 3 – heat exchanger (cooling loop), 4 – adsorber, 5 – vacuum chamber, 6 – evaporator, 7 – condenser, 8,9 – thermocryostats.