An advanced solid sorption chiller using SWS-1L

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Abstract

In this paper, the experimental testing on an advanced solid sorption chiller based on a heat exchanger coated with a compact layer of SWS-1L (CaCl2 in mesoporous silica gel) is presented. The experimental results showed a specific power of 150–200 W/kg of adsorbent and a cycle time of 10–20 min. These values are sensibly better (i.e. one order of magnitude different) than those measured in the same unit working with a SWS-1L pelletised bed. The cooling COP ranged between 0.15 and 0.3, depending on the operating conditions.

Keywords: Adsorption; Air conditioning; SWS; Selective water sorbent; Coated sorbent bed

1. Introduction

A typical SWS is a two-component material based on a porous host matrix with an inorganic salt inside its pores. Various SWSs have been synthesised at the Boreskov Institute of Catalysis and studied in collaboration with the CNR-ITAE [1–3]. A comprehensive evaluation of their applicability in solid sorption cooling/heating is presented in Ref. [4] where it was shown that the SWS-1L (CaCl2 in mesoporous silica gel) represents the most promising composite sorbent for application in solid sorption refrigeration (water chilling). In particular, a theoretical cooling COP of about 0.7 (single bed cycle) was calculated at evaporation and condensation temperatures 10 and 35 °C, respectively. This value is higher than that obtained with traditional adsorbents (zeolite, silica gel, etc.) working with the desorption temperature as low as 90–100 °C. Furthermore, the low SWS-1L desorption temperature allows to use this material for those applications in which a low grade heat is available (solar energy, waste heat utilisation, trigeneration, etc.). These, at the moment, represent the most promising fields of application for the development of solid sorption machines competitive with absorption systems. In order to evaluate experimentally the performance of SWS-1L in a sorption chiller, a lab-scale unit working with a pelletised bed of SWS-1L was realised and tested, as reported in Ref. [5]. The results obtained in that work showed a cooling COP of 0.4–0.6, confirming that the use of SWS-1L can provide high thermodynamic performance. Unfortunately, the not optimised design of the heat exchanger of the sorbent bed, and the poor heat exchange properties of the grain-shaped SWS-1L, led to a poor dynamics of the cycle (i.e. long cycle duration), so that, low values of the specific power were measured (<40 W/kg). However, the interesting result found and the good perspective of improving the performance, encouraged us to continue this research activity.

Consequently, in this paper an innovative adsorbent bed is presented and tested. The bed has been realised according to the methodology developed by the CNR-ITAE and described in [6,7]. It consists of a
lightweight finned tubes heat exchanger coated with a SWS-1L compact layer. This configuration allows to improve the heat transfer through the adsorbent bed and, thus, to increase the specific power of the chiller (providing that the adsorbent bed shows a good interparticle macroporosity). The aim of the experimental testing presented in this work is to find out the real benefit of this advanced bed compared to the “traditional” pelletised one.

2. Experimental

2.1. Description of the sorbent bed

Fig. 1 shows the advanced adsorbent bed realised. It consists of a finned tubes heat exchanger with the external surface coated by a compact layer of SWS-1L with the salt content 33.7 and 25 wt.% of bentonite clay as binder. The composition of the coating was optimised in order to have a good compromise between mechanical strength and porosity of the layer (to avoid mass transfer limitations). Furthermore, it was found that the preparation procedure of the coating does not affect the SWS-1L sorption properties. Several T-type thermocouples inserted inside the SWS-1L coating can be seen in the figure. The mean temperature measured was considered as the temperature of the bed during cycling. The heat exchanger was assembled using special aluminium alloy finned tubes, in which the fins and the tube are a single body. The other components (flanges, fittings, etc.) were also made of an aluminium alloy. In this way, the inert weight was reduced. The main features of the bed are resumed in Table 1.

2.2. Description of the experimental set-up

Fig. 2 shows the scheme of the lab-scale chiller used to test the above described sorbent bed. It consists of a vacuum chamber connected to an evaporator and a condenser, that are water/water tubular heat exchang-
Table 1
Main features of the coated heat exchanger

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total metal mass, kg</td>
<td>6.08</td>
</tr>
<tr>
<td>Total SWS mass, kg</td>
<td>1.75</td>
</tr>
<tr>
<td>Total volume, dm³</td>
<td>8.6</td>
</tr>
<tr>
<td>Length, m</td>
<td>0.56</td>
</tr>
<tr>
<td>Tube diameter, mm</td>
<td>16</td>
</tr>
<tr>
<td>Number of tubes</td>
<td>11</td>
</tr>
<tr>
<td>Heat exchange area, m²</td>
<td>~1.7</td>
</tr>
<tr>
<td>Mass SWS/mass metal</td>
<td>0.29</td>
</tr>
</tbody>
</table>

where the $T_{in} - T_{out}$ refers to the difference in temperature between the inlet and outlet of the external heat transfer fluids of the adsorbent bed and of the evaporator. Consequently, the obtained $P_S$ and COP are indexes of the real useful effect provided by the chiller, that are influenced not only by the thermodynamic and dynamic properties of the SWS-1L, but also by: (1) the efficiency of the heat exchangers and of the evaporator; (2) the heat capacity of the inert masses; (3) the heat losses. Another important parameter experimentally determined during the isosteric phases is the global heat transfer coefficient $U$ of the bed, defined as

$$U = \frac{m_s c_p}{\Delta T_{f-s}}$$

where $\Delta T_{f-s}$ refers to the difference in temperature between the external heat transfer fluid and the adsorbent. This parameter, which accounts for the quality of the heat transfer from (or to) the external heat transfer fluid and the SWS-1L coating, gives a quantitative information about the improvement of the heat transfer with respect to the pelleted bed.

3. Results and discussion

The tests were carried out according to the typical operating conditions of a sorption chiller [8]. The testing procedure consisted of four steps: (1) the isosteric heating: the sorbent bed (closed volume) is heated by the external fluid until reaching the pressure of condensation (inlet temperature of the external fluid $T_{inbed} = 90–100$ °C); (2) the desorption phase: condenser and sorbent bed are connected and the bed is heated until its mean temperature reaches $T_{des} = (T_{inbed} - 5$ °C); (3) the isosteric cooling: the sorbent bed is cooled until reaching the pressure of evaporation (inlet temperature of the external fluid $T_{inbed} = 15–20$ °C); (4) the adsorption phase: the connection between evaporator and sorbent bed is open until the mean temperature of the bed reaches $T_{ads} = (T_{inbed} + 10$ °C). More details about the thermodynamics of the adsorption cycle can be easily found elsewhere [8].

A typical experimental cycle ($T_{inev} = 8$ °C, $T_{incon} = 35$ °C, $T_{inbed} = 100–20$ °C) is presented in Fig. 3 in the Clapeyron diagram, which relates the equilibrium pressure and temperature at fixed water content. In the figure the experimental curve is plotted on the isosteric chart of the pure SWS-1L which was measured at the equilibrium conditions by a thermogravimetric technique [1].

It is evident that the isosteric (heating and cooling) and isobaric (ad/desorption) phases follow satisfactorily the theoretical cycle. An important aspect to be mentioned is that the amount of water effectively evaporated was about 50–70% of the change of uptake that can be
evinced from the adsorption phase plotted on the isosteric chart. This effect is connected to the very quick thermal cycle due to the high thermal efficiency of the bed which is faster than the mass transfer processes. Fig. 4 refers to the same experiment and shows the behaviour of the average temperature and of the pressure of the bed during 45 min of testing. Some important considerations can be drawn: (1) the total cycle time is 10 min (less than 60 s for isosteric heating/cooling and less than 5 min for each desorption/adsorption phase), (2) the difference in temperature between sorbent bed and external fluid is very small, which is an indication of good heat transfer, (3) the pressure change inside the bed has a behaviour coherent with the evolution of temperature (quick increase/decrease during isosteric phases, almost constant during condensation/evaporation).

Fig. 5 shows the instantaneous cooling power extracted from the evaporator (i.e. the useful effect) and the power supplied to/extracted from the bed. The intermittent useful effect produced is due to the single bed configuration of the machine. During the adsorption phase, the instantaneous useful effect is about 400 W/kg of pure SWS (binder excluded), while the instantaneous power supplied during the desorption is about 1500 W/kg. The specific cooling power calculated considering the total cycle time (Eq. 1) is $P_S = 150 \text{ W/kg}$. The corresponding cooling COP (Eq. 2) is about 0.25. Several tests were carried out in the operating conditions at which SWS-1L showed the optimal performance [9]: $T_{\text{in}_{\text{ev}}} = 7–12^\circ\text{C}, \quad T_{\text{in}_{\text{con}}} = 35^\circ\text{C}, \quad T_{\text{in}_{\text{ads}}} = 15–20^\circ\text{C}, \quad T_{\text{in}_{\text{des}}} = 95–100^\circ\text{C}$. In Table 2 the obtained results are resumed and compared with those obtained using a pelletised bed [9].

It is evident that the coated heat exchanger surely presents better heat transfer properties than the pelletised bed. In fact, the cycle time is much shorter and, consequently, the specific power $P_S$ is one order of magnitude higher. The improvement of the heat transfer through the bed, is confirmed by the value of the global heat transfer coefficient $U$, which is higher for the coated heat exchanger. Concerning the COP, the values measured are lower with respect to the pelletised configuration. This is probably due to the short duration of the adsorption–desorption phase which limits the effective amount of refrigerant (water vapor) exchanged between adsorbent bed and evaporator/condenser. Indeed, it was found in [10] that the typical time of water adsorption on SWS-1L loose grains of 1.2–1.6 mm size at
$P \approx 20 \text{ mbar and } T = 59 \text{ °C is 6–8 min (90% of equilibrium water loading), that is longer than the adsorption phase time. However, the values of COP measured are good enough, considering the single bed configuration of the lab scale prototype. A sensible increase in COP can be obtained considering a twin bed configuration with heat (and/or mass) recovery. Optimisation of the design of the external circuits, heat exchanger, thermal capacity of the heat transfer fluids, could also further improve the performance of the chiller. Finally, after about 100 cycles, the coating still presents the same mechanical and sorption properties; No traces of corrosion were found as well. However, the hydro-thermal stability of the coating has to be verified after a larger number of cycles. The next efforts in our experimental activity will be addressed in these directions.

4. Conclusions

The experimental testing on the advanced solid sorption chiller based on the heat exchanger coated with a compact layer of SWS-1L (CaCl$_2$ in mesoporous silica gel) was presented. The experimental results showed a specific power of 150–200 W/kg of adsorbent and the cycle time of 10–20 min. These values are sensibly better than those measured before on the SWS-1L pelletised bed. The effective cooling COP ranged between 0.15 and 0.3, which is about the 30% of the theoretical value. Consequently, further efforts must be done in order to optimise the design of the whole adsorption chiller and to find the optimal compromise between heat and mass transfer properties of the coating layer.

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References