

HYDROPHOBIC ZEOLITE/METHANOL: EXPERIMENTS ON A LAB SCALE REFRIGERATION SYSTEM WITH A THERMALLY EFFICIENT COATED HEAT EXCHANGER

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Abstract

In this paper, the experimental results of a lab scale adsorption chiller working with hydrophobic Y zeolite – methanol are presented and discussed. The main feature of this chiller is the innovative adsorbent bed consisting in a tube and shell heat exchanger (HEX) in which the finned tubes are coated with a zeolite layer. In this way, the interesting sorption properties of the Y type zeolite and the good heat transfer quality of the coated HEX are joined in an advanced sorption machine which requires low temperature heat source.

The experimental results on the device show a specific power of 40-65 W/kg of adsorbent (binder included) and a cycle time of 10-20 minutes depending on the working conditions. Such values are sensibly better than those measured on the same chiller but using a traditional pelletised bed.

KEYWORDS

Zeolite, methanol, adsorption, cooling, heat transfer enhancement

INTRODUCTION

The use of hydrophobic zeolite as solid sorbent and methanol as refrigerant has been recently proposed for application in sorption machines for cooling/heat pumping [1, 2]. The use of methanol allows to work at higher working pressure (100–400 mbar) and lower regeneration temperature (<100°C) with respect to the water. Furthermore, the freezing point below 0°C allows to use the machine in cold climate countries. On the other hand, the zeolite CBV 901 is a special hydrophobic zeolite whose main feature is that the methanol sorption occurs mostly in a narrow range of relative pressure (p/p_0 between 0.1-0.2, being p_0 the adsorbate saturation pressure) [3]; the corresponding Clapeyron diagram presents an extremely small spacing between isosters in the temperature range of interest (40-80°C), as discussed in [4]. In the same paper, and according to the point of view of several researchers, it has been also put in evidence the necessity to try alternative solutions to the traditional pelletised bed to increase the heat transfer and, as a consequence, the specific power of the machine.

For this reason, in the present work a special coated heat exchanger, installed in a full lab-scale sorption chiller, is presented. The results of the experimental activity on such device are presented in terms of cycle time and specific cooling power.

Afterwards, a set of test with a grain shaped bed of CBV901 was carried out in the same operating conditions giving the opportunity to compare the two bed configurations.

EXPERIMENTAL ACTIVITY

Description of the sorbent bed

The main feature of the lab-scale chiller is the innovative adsorbent bed with enhanced heat transfer properties. It consists of a finned tubes heat exchanger with the external surface coated by a thin zeolite layer; inside the tubes a fluid provides/removes heat from the adsorbent material.

The coating procedure, realised according to the methodology developed by the same authors and described in ref. [5], involves a few steps: I) preparation of an aqueous suspension of zeolite powder and a 30 wt.% of binder, II) homogenisation of the suspension via ultrasonic treatment and simultaneous mechanical stirring, until obtaining a dense slurry III) deposition of the slurry on the tube surface and between the fins (pre-treated to clean the surface from possible impurities) by dip coating technique; IV) final thermal treatment at high temperature (about 200°C) which allows the removal of residual solvent and the consolidation of the zeolite layer over the metal surface.

Following the above described technique, the tubes were prepared and then assembled to form the adsorbent bed shown in figure 1. The tubes and the fins are in stainless steel AISI 304 type; the inlet – outlet tubes for the external heat transfer fluid can be easily seen in the picture.

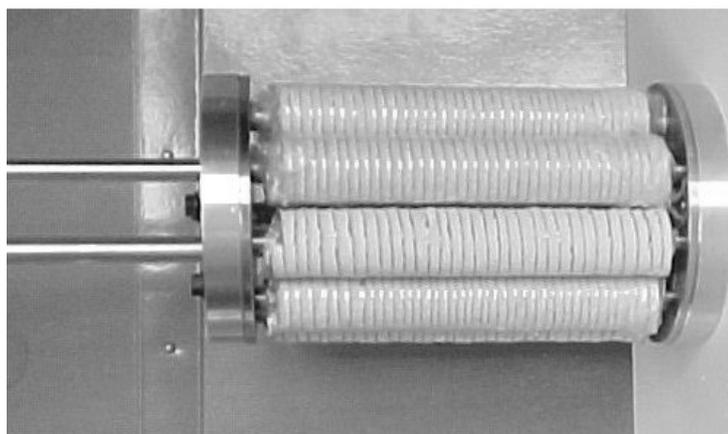


Fig. 1. Finned tubes heat exchanger coated with zeolite CBV-901

The weight ratio of the metal of the heat exchanger over the adsorbent is about 3. This rather high value is due to the not optimisation of the device, because one of the aims was the comparison with a similar bed in which the adsorbent is in pelletised shape. The coated tubes showed good mechanical properties with a compact layer of zeolite without surface cracks and dust production. Furthermore, it was verified by re-measuring the sorption isobars, that the preparation procedure and the binder do not affect the sorption properties of the pure zeolite powder.

Description of the experimental unit

In figure 2 the whole lab-scale chiller is depicted, showing the above described coated bed hold in a vacuum chamber connected to the evaporator and to the condenser. Both the evaporator and condenser are water/water tubular heat exchangers in which the heating/cooling fluid flows inside tubes.

An external circuit allows the heating/cooling of the adsorbent material, the heat transfer fluid is pure glycol, which allows to reach both the standard desorption temperature (<100°C) and the full regeneration of the material at T=150°C. The temperatures of the condenser, evaporator and of the heating/cooling fluid are regulated by means of thermocryostats. A set of T-type thermocouples, pressure sensors and flowmeters are placed in proper positions to measure the operating conditions of the whole machine.

The experimental unit allowed to perform different sorption cycles according to the standard operating conditions of a chiller. Being the experimental unit a single bed system, the cooling effect was intermittent.

A real-time data acquisition system connected to PC was used in order to record the time evolution of the temperature and mass flow of the heating/cooling fluids and of the temperature and pressure of the

sorbent bed, condenser and evaporator. The accuracy of the temperature, pressure and mass flow measurement devices were respectively 0.03°C , 0.1 mbar and 0.1 l/min . The measured parameters allowed to calculate the energy exchanged during each step of the cycle and the useful cooling effect. In particular, the cooling power was calculated as ratio between the useful cooling effect (i.e. the energy supplied to the evaporator) and the total cycle time.

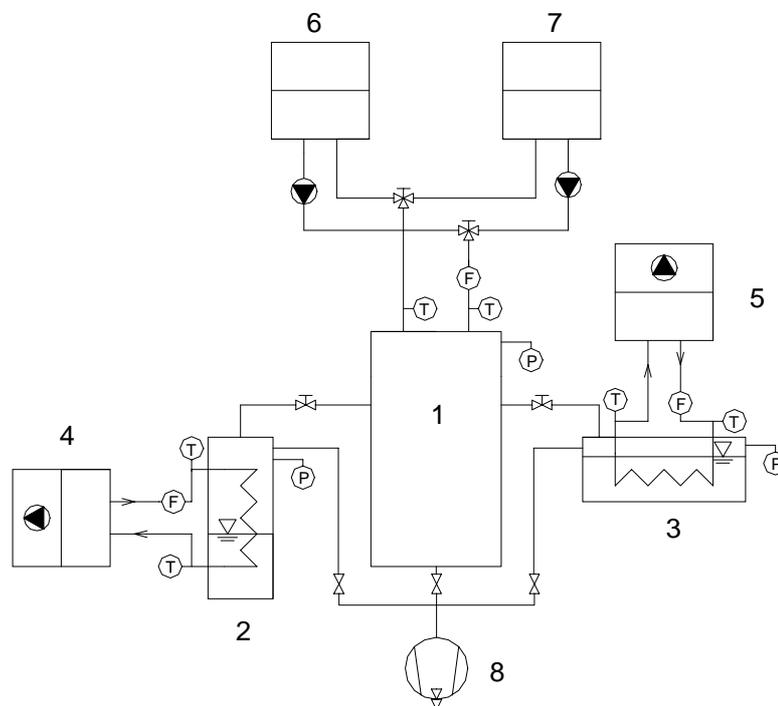


Fig. 2. Scheme of the experimental installation
 1 adsorbent bed, 2 condenser, 3 evaporator, 4-5 evaporator – condenser thermocryostats, 6-7 heating – cooling fluid thermostated baths, 8 vacuum pump, F flow-meters, T temperature sensors, P vacuum gauges.

RESULTS AND DISCUSSION

The tests were carried out with the aim to simulate sorption cooling cycle in different working conditions ($-2 < T_{ev} < 15^{\circ}\text{C}$, $35 < T_c < 45^{\circ}\text{C}$, $70 < T_d < 100^{\circ}\text{C}$).

In Figure 3, two typical experimental cycles are presented in the isosteric diagram, that relate equilibrium pressure and temperature at fixed adsorbate content.

Regarding the isosteric diagram, it is evident the extremely close spacing between isosters in the temperature range of interest, which means a large variation of methanol uptake inside the thermodynamic cycle.

The experimental cycles plotted in the diagram correspond to typical sorption cycles for ice making and air conditioning, putting in evidence that the area of strong methanol variation is inside the cycles. Hence, from the thermodynamic point of view, this pair can be used for the applications above described with a desorption temperature as low as 70 and 85°C respectively.

Furthermore, from this diagram it was possible to obtain useful information regarding the heat and mass transfer characteristics of the bed. The closed volume heating/cooling phases followed satisfactorily the theoretical isosters, small differences are probably due to the thermal inertia of the system.

During the isobaric phases of the air conditioning cycle, the pressure inside the bed is almost constant

and equals to that fixed in the condenser/evaporator. This means that there is uniform methanol diffusion through the zeolite layer and that this step is controlled by the rate of the heat extracted from the bed rather than by the mass transfer limitations.

On the contrary, the adsorption phase of the ice making cycle shows a pressure decrease of about 10 mbar, so that the mass transfer resistance becomes more relevant. This is probably due to the very low partial pressure of the methanol at that temperature that leads to a minor vapour flow in the porous solid. However, the latter effect is enhanced in terms of visibility by the adopted log scale and in fact did not affect the overall cycle dynamic. So, it can be concluded that the 10 mm layer of compact zeolite is characterized by quite sufficient mass transfer properties.

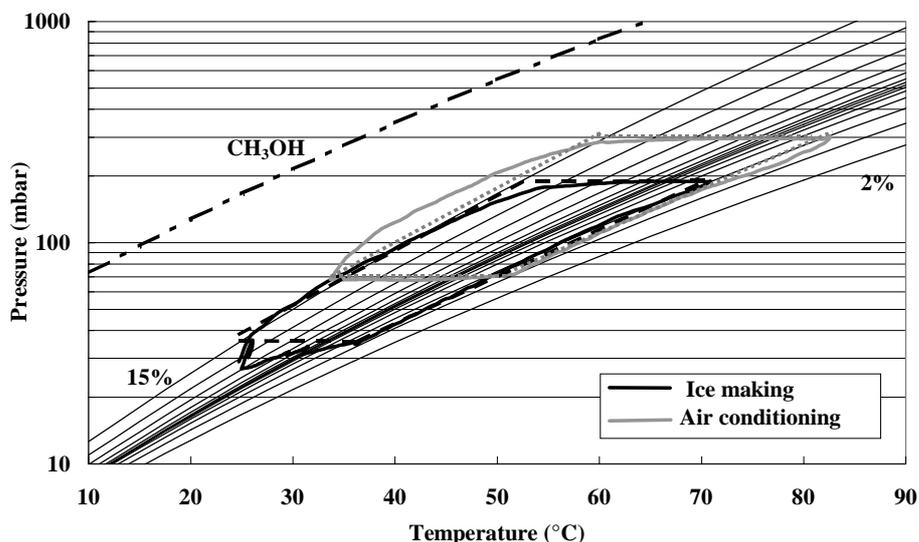


Fig. 3. Zeolite - methanol isotherms and thermodynamic cycles for air conditioning and ice making; dotted lines refer to the ideal cycles

The experimental result that needs a special remark is the very short cycle time measured (10-23 min, depending on the operating conditions), due to the improved heat transfer characteristics of the bed. The benefit of a very short cycle time can be directly translated to good dynamic performance of the chiller.

Fig. 4 shows the behaviour of the average temperature of the bed during a typical test ($T_{ev}=10^{\circ}C$, $T_{con}=35^{\circ}C$, $T_{reg}=85^{\circ}C$), carried out both on the advanced coated bed and on the traditional pelletised one.

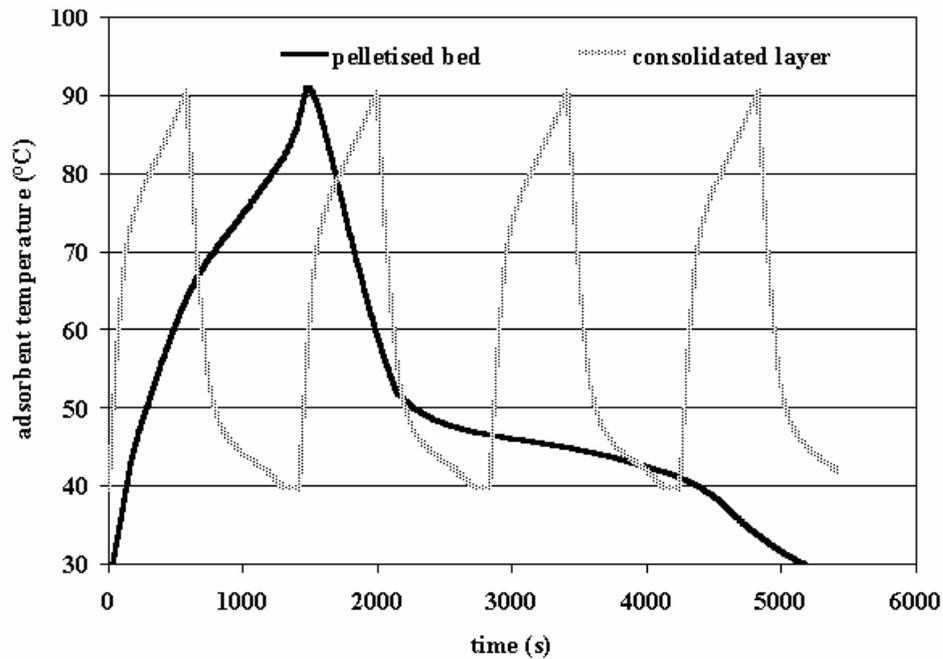


Fig. 4. Behaviour of the bed temperature vs. time during a test

The isosteric and isobaric phases can be easily evinced by the change of the slope of the temperature profile dT/dt due to the ad/desorption phenomena. The most important point is that, in the time required for one cycle of the pelletised bed, almost 4 cooling cycles of the bed with coated heat exchanger can be carried out.

Fig. 5 reports the instantaneous cooling power extracted from the evaporator (i.e. the useful effect). The intermittent useful effect produced is due to the single bed configuration of the machine. It is evident that the coated heat exchanger allows to obtain a higher power in a shorter time with respect to the pelletised bed.

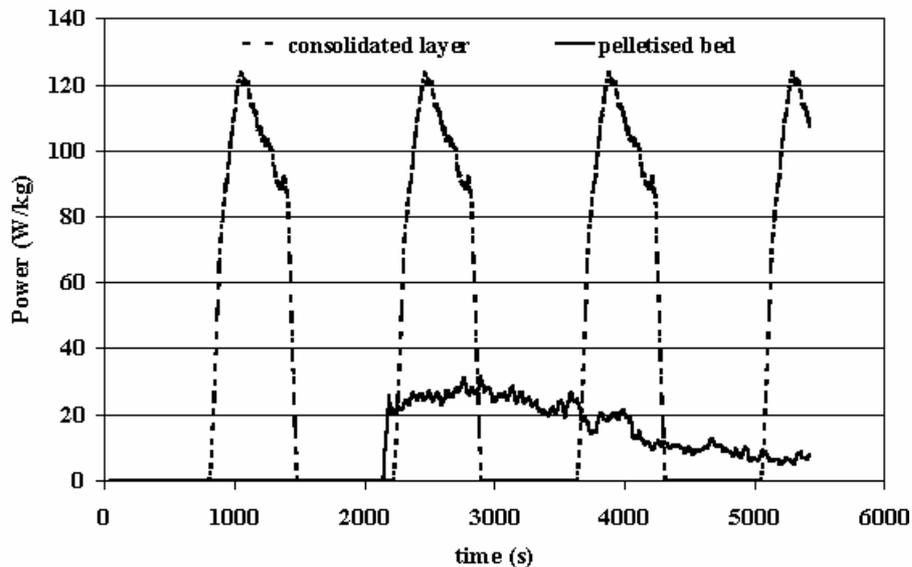


Fig. 5. Specific cooling power as a function of time

Hence, assuming a double bed system, a continuous useful effect of 100-110 W could be obtained, five times higher than that corresponding to the pelletised bed. Such considerations are extended in Tab. 1, in which the specific powers obtained from the experimental results as a function of the desorption temperature and for different temperature of condensation and evaporation are presented.

Table 1. Average specific cooling power vs. regeneration temperature for different T_{ev} , T_c .

Sp. cooling power W/kg	T evap. °C	T cond. °C	T des. °C
59.9	10	35	80
62.5	10	35	85
60.0	10	35	90
53.2	10	40	85
54.4	10	40	90
53.4	10	45	95
42.2	5	35	90
39.9	5	40	90
62.8	15	40	90
43.5	-2	25	75

The highest values of the specific cooling power (60-63 W per kg of coating adsorbent including the inert binder) were obtained for regeneration temperature of 80-90°C and considering the evaporation - temperature of 10-15°C. Instead, for lower evaporation temperatures (that means higher ΔT between evaporator and condenser), the specific power decrease down to 40-45 W/g.

Consequently, the pair hydrophobic zeolite – methanol sounds attractive for application in the field of the air conditioning, while for other applications like ice making or food storage seems to be less effective. If one considers also the quick cycle time and the low desorption temperature, the best application for this adsorber probably is the automotive air conditioning in which the driving force is the heat coming from the cooling jacket of the engine at ~ 90°C.

To complete the evaluation of the performance of the unit, the gross COP was calculated as ratio between the energy extracted from the evaporator and the energy furnished by the external heat source at high temperature. The values measured in all tests ranged between 0.10 and 0.12. This is due to different reasons: i) the low latent heat of methanol that is about half than that of water, ii) the high thermal capacity of the inert masses in the unit, iii) the not optimized design of the evaporator and condenser. A further increase of the COP could be obtained improving the design of the machine or using heat recovery cycles; anyway, it is not possible to overcome the intrinsic thermodynamic properties of methanol, which lead to theoretical COP of 0.28 (single bed) or 0.32 (double bed – heat recovery) [4].

CONCLUSIONS

The results of the experimental activity on the innovative chiller show that, despite the low cooling COP measured (due to the high mass ratio between metal and zeolite) a very quick cycle and thus a high specific power is obtained. In particular, a specific power of 40-65 W/kg of adsorbent (binder included) and a cycle time of 10-20 minutes has been measured depending on the chosen working conditions. Such values are sensibly higher than those measured during another set of tests on the same machine but with a traditional pelletised bed.

The better results are evidently due to the high global heat transfer coefficient of the coated HEX. Consequently, the pair zeolite CBV-901/methanol sounds very attractive for those applications (like automotive air conditioning) in which the COP is not mandatory but that require quick sorption dynamic and high specific power.

Acknowledgements

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