Performance analysis of a cascading adsorption cycle powered by high temperature heat sources for low temperature cooling in hot climates

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ABSTRACT

Cascade adsorption refrigeration technology using high temperature driving heat is a very promising option for low temperature cooling applications due to the large temperature difference between the heat source and the cold distributed. The present work carried out a feasibility and parametric study in order to analyse the functioning of a cascading adsorption cycle using the working pair zeolite/ammonia in beds operating at high temperatures and activated carbon/ammonia in those operating at low temperatures. At the nominal thermal conditions, namely heating, condensing and evaporating temperatures of 280 ℃, 35 ℃ and (-5) ℃, respectively, the coefficient of performance (COP) and the specific refrigerating capacity (SCP) of the cycle were 0.53 and 67.1 W.kg^{-1}. When

the driving temperature is varied from 260 ℃ to 320 ℃, the COP increases by 57% and the SCP by 36%. The performance of the cascading adsorption cycle at negative evaporating temperatures is very satisfactory.

Keywords: Adsorption refrigeration; cascading cycle; low temperature cooling; activated carbon/ammonia; zeolite/ammonia

HIGHLIGHTS

- A cascading adsorption cycle, driven by high temperature heat sources, is proposed for low temperature cooling.

- The cascading adsorption refrigeration cycle investigated uses zeolite/NH_3 and activated carbon/NH_3 as working pairs.

- A significant effect of heating and condensing temperatures on the performance of the adsorption cycle is observed.

- COP and SCP are 0.53 and 67.1 $W.kg^{-1}$ at heating, condensing and cooling temperatures of 280 ºC, 35 ºC and -5 ºC, respectively.

INTRODUCTION

The global refrigeration market is constantly expanding and changes are taking place as international rules and regulations come into force in an effort to halt the destruction of the ozone layer and to put a stop to greenhouse gas emissions. Currently, most of the demand in the refrigeration market is covered by vapor compression systems powered by electrical energy produced from primary fossil energy sources with high CO_2 emissions. These refrigeration systems consume about 30% of the world's total energy consumption [1, 2].

Sorption refrigeration technology is an alternative to vapor compression refrigeration systems. The nature of the refrigerant used and the energy consumed means that it is more environmentally friendly and consequently a promising solution. These refrigeration systems are commonly driven by heat sources such as solar energy or waste heat. The idea of using an adsorption refrigeration machine was proposed by Tchernev [2] who studied a solid sorption cycle using the zeolite/water pair. There are two configurations of adsorption refrigeration cycles: single bed intermittent cycles (sorption element) and continuous cycles. The operating principle of the first configuration is the same as for a conventional vapor compression system, with a refrigerant that vaporizes at low temperatures to produce cold and condenses at higher temperature for heat rejection. The mechanical compressor is replaced by an adsorption reactor which acts as a generator. The major problem of intermittent cycles is the discontinuity of cold production and the low value of the coefficient of performance (COP), which is in some cases less than 0.1. The second configuration was designed to improve the efficiency of the adsorption refrigeration cycle and overcome the intermittency of cold production by using two or more beds. Continuous refrigeration effect can be achieved by different configurations of the adsorption cycle [1, 3-4], namely: (i) Adsorption refrigeration cycles with heat recovery; (ii) Adsorption refrigeration cycles with mass recovery; (iii) Multi-stage adsorption refrigeration cycles and cascading cycles; (iv) Thermal wave cycles; (v) Convective thermal wave cycles; (vi) Hybrid cycles.

Adsorption refrigeration systems exhibit a simple control and can be operated at significantly lower vibrations compared to conventional vapour compression systems. Cascading cycles can be operated by heat sources at temperatures over 200 °C without corrosion problems [5-6]. In addition, they are applied when the temperature difference between the heat source and the evaporator/refrigerator space is high. Moreover, their use can be extended to applications requiring negative cold temperatures [1, 7]. Cascading adsorption refrigeration systems were the subject of several theoretical and experimental investigations [1, 7-8].

Meunier [9] theoretically analysed the performance of four configurations of cascading adsorption refrigeration systems at different regeneration and evaporating temperatures. The configurations consisted of a zeolite/water double effect cycle and three low temperature activated carbon/methanol cycles, stimulated by a high temperature zeolite/water double effect cycle. The results showed that the performance of these cycles was very satisfactory in cogeneration mode for chilled water for cooling and hot water for heating. Douss and Meunier [10] proposed a cascading adsorption cycle using two different working pairs, namely zeolite/water and active carbon/methanol. This cycle consisted of three adsorbers, two condensers and two evaporators. The adsorber of the lower cycle, working with activated carbon, was heated by the heat released by the two absorbers of the upper cycle operating with zeolite. The authors reported an experimental COP of 1.16. Stitou et al. [11] investigated several cascading cycles by coupling two sorption processes in the same refrigeration cycle, namely a solid/gas thermochemical reaction process and a liquid/gas cascading absorption process, to increase the COP by 30% compared to double-effect absorption refrigeration cycles.

Oliveira et al. [12] conducted an experimental study of an adsorption refrigeration cycle consisting of four beds, a condenser and an evaporator, using activated carbon/ammonia as a working pair. The experiments were performed at two desorption temperature levels, with and without mass recovery. The results showed that the desorption rate obtained by the mass

recovery cycle was 42% and 37% at desorption temperatures of 85 ºC and 115 ºC, respectively. These desorption rate values were higher than those obtained with the cycle without mass recovery.

Douss and Meunier [13] carried out an experimental study of a cascading adsorption heat pump. The adsorption cycle consisted of a two adsorber zeolite-water high temperature stage and an intermittent active carbon-methanol low temperature stage. Driving heat was supplied to zeolite adsorber and active carbon adsorber was heated by heat recovered from the zeolite adsorber. Evaporators of both basic cycles operated at the same temperature and contributed to the evaporating load. The experimental results showed that the cooling COP was 1.06, which was significantly higher than the COP of an intermittent cycle (~0.5) and more than the COP of a two adsorber zeolite water cycle (~0.75).

Liu and Leong [14] proposed improvements in the cascading cycle reported by Douss and Meunier [13]. They numerically investigated a novel cascading cycle consisting of two zeolite adsorbent beds and a silica gel adsorbent bed with only one type of refrigerant (water). This cycle was simpler than that of Douss and Meunier [13] because it required only one condenser and one evaporator. Morever, the COP for this cycle was in the order of 1.3, which was more than twice that of an intermittent adsorption cycle (about 0.5) and higher than that of a cycle with heat and mass recovery (about 0.8). Uyun et al. [15] analysed the possibility of improving the performance of a cascading cycle with the use of a new mass recovery cycle, in which the driving temperature was varied between 90 ºC and 130 ºC. To assess the improvement in performance in terms of specific cooling capacity and coefficient of performance, a comparison with the conventional single-stage adsorption refrigeration cycle was carried out. The authors concluded that cascading adsorption cycles produced higher COP values (>1) but lower PCS values compared to the conventional single-stage adsorption cycle. Marlinda et al. [16] presented a numerical study of a double-effect adsorption refrigeration cycle, in which the

condensing heat released in the upper cycle was used as the driving heat source in the lower cycle. The results showed that the COP of the double-effect adsorption cycle was higher than that of the conventional single-stage adsorption cycle at an average chilled water temperature of 9 ºC and heat source temperatures ranging from 100 ºC to 150 ºC. However, the CPS of the double-effect adsorption cycle was significantly lower.

Dakkama et al. [7] proposed a cascading cycle with an integrated condenser and evaporator for cooling purposes using low temperature heat sources. The authors used five different combinations for the working pair, namely ATO/ethanol + Maxsorb/R507A; Maxsorb/R134a + Maxsorb/propane; ATO/Ethanol + Maxsorb/propane; ATO/ethanol + AC-35/methanol; and Maxsorb/R134a + Maxsorb/R507A. The results showed that Maxsorb/R134a + Maxsorb/propane produced a higher coefficient of performance than the other combinations.

Although all the above mentioned investigations are very useful for cooling applications, these adsorption cycles are still subject to some functional limitations. They cannot effectively use the potential of high temperature heat sources for low temperature cooling in warm climates. To correct this shortcoming, a feasibility study of a novel adsorption cascading cycle was carried out in the present work. This adsorption cycle uses ammonia as refrigerant and activated carbon and zeolite as adsorbents. The use of these working pairs is a key factor for the optimization of the adsorption refrigeration cycle proposed for applications requiring cooling down to temperatures as low as -50 ºC when operating in hot climates. This configuration of adsorption cycles would allow for the use of solar thermal energy. The huge potential available in arid and semi-arid areas for this energy could greatly benefit those that are not connected to the electricity grid or do not have a continuous supply of electricity to ensure the conservation and preservation of foodstuffs, vaccines and pharmaceutical products and ice making.

In this paper, a numerical analysis was carried out to study the effect of the main operation parameters on the performance of a cascading adsorption cooling cycle powered by high temperature heat sources for low temperature cooling in hot climates. The working pair selected for the cycle operating at low temperatures was activated carbon/ammonia and zeolite/ammonia was selected for the cycle operating at high temperatures. These working pairs are particularly well adapted to low temperature refrigeration processes using high temperature heat sources for regeneration and high temperature cooling mediums for heat dissipation. This combination of the cycle configuration and working pairs has not previously been investigated in the open literature at the thermal operating conditions considered in the present work.

SELECTION OF THE WORKING PAIRS

In cascading adsorption cycles, the main idea is to perform desorption/condensation and evaporation/adsorption processes at different temperature and pressure levels [8]. The choice of a refrigerant is based on technical, ecological and economic criteria. It needs to have a large latent heat of vaporization in order to increase the refrigeration load [17]. As regards the adsorbent, it should have a high adsorption capacity of the refrigerant at ambient temperatures and a reasonable pressure corresponding to the equilibrium pressure prevailing in the evaporator. It should also have a low adsorption capacity at high temperatures and pressure and be compatible with the refrigerant [18].

Several investigations were reported in the open literature on adsorption refrigeration machines. Generally, three types of adsorbent/adsorbate pairs were recommended for adsorption refrigeration systems, namely water, ethyl alcohol, methyl alcohol and ammonia as refrigerants and activated carbon, silica gel and zeolite as adsorbents. Water and methanol adsorption systems operate at subatmospheric saturation pressures, which negatively affect the operation of the system (air intake). In the case of ammonia, small leaks may be tolerated for

some time, but its saturation pressure of 13 bar at a condensing temperature of 35 °C is very demanding [18].

The present work deals with applications requiring cooling at low temperature using high temperature driving heat, Therefore, the refrigerant to be used in the adsorption cycle investigated should be stable within the temperature range used in the cycle, i.e. between -5 ºC and 280 ºC. Among the refrigerants used in the literature, ammonia seems to be the most suitable refrigerant for the operating conditions of the adsorption cycle of the present work. It has a good energy density, its enthalpy of vaporization is about 1240 kJ.kg^{-1}, it is stable over a wide temperature range, which is of interest for low temperature refrigeration cycles, and it only solidifies at -77 ºC. Moreover, it is abundant and moderately expensive. As long as the safety standards for its use are met, it is considered a natural refrigerant.

Zeolite was mainly used as an adsorbent for ammonia in adsorption cycles operating at high temperatures, while silica gel and activated carbon were usually used as an adsorbent in cycles operating at low temperatures [15]. In addition, the operation of adsorption cycles using zeolite is optimal when the temperature of the driving heat source is above 150 ºC. Zeolite has a higher adsorption heat than other adsorbents, such as silica or activated carbon [19].

In the present work, the working pair selected for the cycle operating at low temperatures was activated carbon/ammonia and zeolite/ammonia for the cycle operating at high temperatures. These working pairs are particularly well adapted to low temperature refrigeration processes, i.e. freezing and ice production, using high temperature heat sources for regeneration and high temperature cooling mediums for heat dissipation. They cover all refrigeration applications requiring cold between -50 ºC and 10 ºC [5-6]. A literature survey on the use of these two working pairs in adsorption refrigeration systems is herein briefly summarized.

Activated carbon/ammonia working pair

Several investigations are reported in the literature on adsorption systems using activated carbon/ammonia [5-6, 18]. Critoph [20] analysed the thermodynamic performance of adsorption cycles using several refrigerants, such as methanol, sulphur dioxide, ammonia, methylamine and formaldehyde, in combination with activated carbon. The best performances were obtained with ammonia and methanol in an adsorption refrigeration machine used to store vaccines in arid zones. Tamainot-Telto and Critoph [21] carried out a theoretical and experimental study on a prototype of an adsorption refrigeration machine using the monolithic activated carbon/ammonia pair. Theoretical results showed that the cooling capacity obtained with monolithic carbon was about 90% higher than that obtained with granular carbon. These results were consistent with the experimental results obtained under the operating conditions of an ice machine working in tropical thermal conditions, i.e. the evaporating and condensing temperature ranges were -20 ºC to 0 ºC and 20 ºC to 45 ºC, respectively. These same authors presented in reference [22] a study of three configurations of a multi-bed adsorption air conditioning system using monolithic carbon and ammonia. The SCP of the appropriate module was 600 W.kg^{-1} adsorbent when the desorption, condensing and evaporating temperatures were 100 ºC, 30 ºC and 5 ºC, respectively.

More detailed investigations on different combinations of activated carbon/ammonia used in adsorption systems for ice making, air conditioning and heat pumps were carried out by Tamainot et al. [23] and Metcalf et al. [24]. They used three cycle configurations, namely single bed, double bed and an infinite number of beds. The generation temperature was varied from 80 ºC to 200 ºC. Simulation results of 26 different combinations of the activated carbon/ammonia pair showed that the best thermal performance was obtained with KOH-AC monolithic coal at a generation temperature of 100 ºC, the cold production being about 66 MJ.m^{-3} (COP=0.45) and 151 MJ.m^{-3} (COP=0.61) for ice making and air conditioning, respectively.

In heat pump mode, the heat production was approximately 236 MJ.m^{-3} (COP=1.50). Therefore, this type of activated carbon was selected for use in the cascading adsorption cycle investigated in the present work.

Zhao et al. [25] determined the optimal adsorbent for different adsorption refrigeration applications after carrying out a comparative study of the thermal conductivity, permeability and equilibrium and non-equilibrium adsorption performance of six samples of three types of carbon. The authors concluded that the cyclic mass of an unbalanced adsorption process was less than that of an equilibrium adsorption process. For freezing operating conditions the cyclic mass was relatively low, the maximum value being in the order of 0.062 and 0.139 kg.kg^{-1} for refrigeration temperatures of 10 ºC and 15 ºC, respectively.

Aghbalou et al. [26] studied an adsorption refrigerator using a detailed model for heat and mass transfer taking place in a cylindrical generator operating with the activated carbon/ammoniac pair. The experimental results showed that the coefficient of performance (COP) was in the order of 0.144. Louajari et al. [27] demonstrated the feasibility of solar adsorption refrigeration in rural areas using the activated carbon/ammoniac pair. The results showed that the cooling effect obtained in the form of ice was between 3.33 and 4.14 kg.m^{-2} for a flat plate solar collector and between 7.16 and 9.94 kg.m^{-2} for a flat solar collector.

Zeolite/ammonia working pair

Shelton et al. [28] determined the coefficient of performance (COP) of an adsorption heat pump using the zeolite/ammonia working pair. The authors reported values of 1.625 and 1.87 for COP at heating temperatures of 212 ºC and 316 ºC, respectively. Vasiliev et al. [2] analysed three types of solid adsorbents; namely zeolite NaX, carbon fibre "Busofit",and "Busofit" with ammonia. The specific cooling capacity obtained was 47 kW.m^{-3} for NaX zeolite, 50 kW.m^{-3} for Busofit fibre coal and 62.7 kW.m^{-3} for Busofit compound. Halim et al. [29] studied ammonia adsorption kinetics on three different adsorbents. The results showed that

ammonia adsorption was better on composite media (24.39 mg.g^{-1}), followed by zeolite (17.45 mg.g^{-1}) and activated carbon (6.08 mg.g^{-1}) and that all adsorbents were well adapted to Langmuir and Freundlich isotherms for ammonia adsorption.

CONFIGURATION AND OPERATION MODE OF THE CASCADING ADSORPTION CYCLE

A schematic representation of the cascading adsorption cycle used in this work is shown in Fig. 1. The cycle consists of three beds, namely two adsorbers (1 and 2) working with zeolite and one adsorber (3) that operates with activated carbon. The heat transfer medium (ammonia) flows through the adsorbers, condenser, evaporator and a storage tank downstream of the condenser. The three adsorbers are driven by a thermal fluid (HXF) heated by the external heat source and circulated by the P1 pump. The cooling fluid (HXF), circulated by the P2 pump, allows for the heat dissipation from the adsorbers in adsorption operation mode. Ten valves are used to control the flow directions of the heating fluid (V_{fh1-8}) and cooling fluid (V_{fc1-2}), and five valves are used to open and close the circuits connecting the three adsorbers (V_{hr1-5}). During the processes of desorption/condensation or adsorption/evaporation the beds are connected to the condenser or evaporator by opening the valves (V_{vc1-2}) or (V_{ve1-2}). The valve (V_{ve1}) located in the circuit connecting the condensate storage tank and the evaporator is an expansion valve. This cascading adsorption cycle operates in four stages. A representation of the theoretical cascading adsorption cycle in the Clapeyron diagram is shown in Fig. 2.

First step

At the beginning of the cycle the adsorbers 1 and 3 are at their maximum temperatures (end of desorption process) and the adsorber 2 is at its minimum temperature (end of adsorption process) (point I, E and C in Fig. 2) where the adsorbent is loaded with a maximum mass of adsorbate. The opening of the mass recovery valves (V_{hr1-4}), connecting adsorbers 1 and 2, allows for the equalization of the pressures of these two adsorbers. This is accompanied by a mass transfer from the adsorber 1 (HP) to the adsorber 2 (BP) (I-J and E-F process). Adsorber

2 is then heated by the heat released in adsorber 1 through an external heating fluid (HXF) and the opening of the V_{fh1-6} valves (F-G-H processes for adsorber 2 and J-K-M for adsorber 1 in Fig. 2). At this point the adsorber 3 is cooled by opening the valve V_{fc1-2} (process C-D-A in Fig. 2).

When the pressure prevailing in adsorber 2 reaches the condenser pressure (Pc), the valves V_{vhr4} and V_{vc2} are opened and the desorbed refrigerant vapour flows to the condenser where it is liquefied and the condensate is stored in the tank. Opening the valve V_{ve1} allows the condensate stored in the tank to expand before entering the evaporator. When the pressures prevailing in adsorbers 1 and 3 reach the evaporator pressure (Pe) the valves V_{vhr1} and V_{ve2} are opened and adsorbers 1 and 3 are then connected to the evaporator.

Second step

During this step adsorber 3 is heated (process A-B-C) by adsorber 1 (process M-E in Fig. 2) (opening of valves V_{fh3-4}, V_{fh7-8}) and adsorber 2 is heated via an external source (HXF) (opening of valves V_{fh1-2} and V_{fh5-6}) (process G-H in Fig. 2).

When the pressure in adsorber 3 reaches the condenser pressure (Pc), the valves (V_{vc1-2}) are opened and adsorber 3 is connected to the condenser. At the same time, the valve V_{vc2} is closed and adsorber 2 is disconnected from the condenser and connected to adsorber 3 by opening the valves V_{hr3} and V_{e2}. The higher temperature adsorbate vapour from adsorber 2 flows through adsorber 3 to the condenser (opening of the valves V_{vc1-2}).

Once adsorbers 1 and 2 are interchanged, the other two steps are identical in processes to the first two ones.

MODELLING OF THE CASCADING ADSORPTION CYCLE

A mathematical model was developed to simulate the dynamic functioning of the cascading adsorption cycle working with the activated carbon/ammoniac and zeolite/ammoniac

working pairs. The governing equations, simplifying assumptions, performance parameters and resolution procedure are described in the following sections.

Equilibrium equations

Various equations were proposed to define the relationship between the adsorption process and the pressure of the vapor to be adsorbed. According to the investigations reported in the open literature, the Dubinin-Radushkevich (D-R) equation appears to be the most suitable expression to describe the adsorption process in the two types of adsorbents considered in the present work [30]

- Activated carbon/ammonia pair

The Dubinin-Astakhov equation used is given by [23]:

$$x = x_0 \exp\left[-K\left(\left(\frac{T}{T_{sat}}\right)^n\right)\right] \qquad (1)$$

Where: x is the ammonia concentration ($kg_{ammonia}.kg_{coal}^{-1}$), T is the activated carbon temperature (K), T_{sat} is the saturation temperature corresponding to the vapor pressure (K). The coefficients x_0, K, n used in this equation are shown in Table 1.

- NaX-zeolite/ammonia pair

The Dubinin-Astakhov equation used is given by [30]:

$$x = 221.2 \exp\left[-1.916 \times 10^{-7} \times \left(T \times \ln\left(\frac{P_{sat(T)}}{P}\right)\right)^2\right] \qquad (2)$$

Where the saturation pressure is defined by [10]:

$$\ln(P_s) = \frac{-2748.39}{T} + 23.03 \qquad (3)$$

x is the amount of adsorbed vapour per unit mass of adsorbent ($kg_{ammonia}.kg_{zeolite}^{-1}$).

Energy balances

The mathematical model developed is based on the Dubinin-Astakhov model equation of state and on the different heat duties exchanged during the thermodynamic cycle (Clapeyron)

of the adsorption refrigeration machine using the activated carbon/ammoniac and zeolite/ammoniac pairs (Fig. 2). A dynamic energy balance was carried out in the three adsorbers of the adsorption cycle and in the two stages of the cycle. Each differential equation was derived from the principle of energy conservation as follows.

First step

Neglecting the external heat losses, the energy balances in the three adsorbent beds are as follows:

- **Adsorbers 1 and 2**

$$\sum m_i \, C_{pi} \frac{dT_{ai}}{dt} = m_z \Delta H \frac{dx_i}{dt} + (m_z Cp_v \frac{dx_i}{dt} ((1-\gamma)(T_{ev} - T_{ai}) + \gamma(T_{ai-1} - T_{ai})) + Q_{fai} \quad (4)$$

Where $\sum m_i \, C_{pi}$ is the total heat capacity of the adsorber, defined by:

$$\sum m_i \, C_{pi} = m_z C_{pz} + m_m C_{pm} + m_z x \, C_{pa} \qquad (5)$$

When i=1, γ=0 and adsorber 1 is connected to the evaporator.

When i=2, γ=1 and heat and mass transfer takes place between adsorbers 1 and 2.

Q_{fai} is the heat exchanged between the HXF heating medium and adsorber i, it is defined by the following equation:

$$Q_{fai} = \dot{m}_f C_{pf}(T_{fi,in} - T_{ai})[1 - \exp(-NTU_i)] \qquad (6)$$

During heat transfer between the two adsorbers 1 and 2, the inlet temperature of the HXF heating medium at the inlet of one adsorber is equal to the outlet temperature of the other, therefore the temperatures of the HXF medium at the inlet and outlet of adsorbers 1 and 2 are as follows:

$$T_{fi,out} = T_{ai} + (T_{fi,in} - T_{ai})\exp(-NTU_i) \qquad (7)$$

and :

$$\begin{cases} T_{f1,in} = T_{f2,out} \\ T_{f2,in} = T_{f1,out} \end{cases} \qquad (8)$$

If we neglect the sensitive heat of the HXF fluid we obtain:

$$Q_{fa1} + Q_{fa2} = 0 \qquad (9)$$

The resolution of equations (7), (8) and (9) gives:

$$Q_{fa1} = -Q_{fa2} = \dot{m}_f C_{pf}(T_{a2} - T_{a1}) \times \frac{[1-\exp(-NTU_1)][1-\exp(-NTU_2)]}{[1-\exp(-NTU_1)\exp(-NTU_2)]} \qquad (10)$$

- **Adsorber 3**

When adsorber 3 is connected to the evaporator, the energy balance is written as follows:

$$\sum m_i' C_{pi}' \frac{dT_{a3}}{dt} = m_{ch}\Delta H' \frac{dx}{dt} + m_{ch}C_{pv}\frac{dx}{dt}(T_{ev} - T_{a3}) + Q_{fa3} \qquad (11)$$

Where Q_{fa3} is the heat exchanged between the HXF heating medium and adsorber 3, it is defined by the following equation:

$$Q_{fa3} = \dot{m}_f C_{pf}(T_{c,in} - T_{a3})[1 - \exp(-NTU_3)] \qquad (12)$$

Second step

- **Adsorbers 1 and2**

$$\sum m_i C_{pi} \frac{dT_{ai}}{dt} = m_z\Delta H \frac{dxi}{dt} + (m_zCp_v\frac{dxi}{dt}((1-\gamma)(T_{ev} - T_{ai})) + Q_{fai} \qquad (13)$$

When i=1, γ=0 and adsorber 3 is heated by adsorber 1.

When i=2, γ=1 and adsorber 2 is heated by the HXF heating medium.

- **Adsorber 3**

A mass transfer is made between the two adsorbers 2 and 3 and the energy balance is written as follows:

$$\sum m_i' C_{pi}' \frac{dT_{a3}}{dt} = m_{ch}\Delta H' \frac{dx}{dt} + m_zCp_v\frac{dx}{dt}\Big|_{a2}(T_{a2} - T_{a3}) + Q_{fa3} \qquad (14)$$

Mass balances

When the adsorber is completely isolated from the other components of the system and consequently mass transfer is not possible, the ammonia vapour contained in this adsorber is either adsorbed in the zeolite or trapped in the various free volumes. The mathematical expression defining the mass conservation in the adsorber is as follows:

$$\frac{dm_{vap}}{dt} + m_{ads}\frac{dx}{dt} = 0 \qquad (15)$$

In the present work, the mass of ammonia vapour is neglected, so the mass balance is expressed by:

$$m_{ads}\frac{dx}{dt} = 0 \qquad (16)$$

Where m_{vap} is the mass of vapour contained in the free volumes and porosities of the adsorber and x is the amount of vapour adsorbed.

Performance parameters of the cascading adsorption cycle

The thermal performances, in terms of coefficient of performance (COP) and specific refrigerating capacity (SCP) associated with the operation of the adsorption refrigeration system under study are defined by [14]:

$$COP = \frac{Q_f}{Q_h} \qquad (17)$$

Q_f is the cooling capacity of the evaporator.

Q_h is the heat power supplied to adsorber 2 during the second step.

Q_f and Q_h are obtained from the following expressions:

$$Q_f = \int_0^{t_c/2}\left[L_v(T_{ev}) - C_{pl}(T_{cd} - T_{ev})\right]m_t\,dt \qquad (18)$$

$L_v(T_{ev})$ is the latent heat of vaporization of ammonia at the evaporating temperature (T_{ev}) [31].

$$L_v(T) = L_0 + L_1 \times T + L_2 \times T^2 + L_3 \times T^3 \qquad (19)$$

C_{pl} is the specific heat of liquid ammonia.

$$Q_h = \int_{t_{st1}}^{t_{c/2}} \dot{m}_f C_{pf} \left(T_{f2,in} - T_{f2,out} \right) dt \qquad (20)$$

m_t is the total cyclic mass of ammonia.

$$m_t = m_z \left. \frac{dx}{dt} \right|_{a1} + n m_{ch} \left. \frac{dx}{dt} \right|_{a3} \qquad (21)$$

$$SCP = \frac{Q_f}{t_{c/2} m_t} \qquad (22)$$

$t_{c/2}$ is the half cycle time.

According to Stitou et al. [11] and Liu and Leong [14], the coefficient of thermal performance (COP) of a cascading cycle is defined as follows:

$$COP = COP_1 + \left(\frac{Q_i}{Q_h} \right) COP_2 \qquad (23)$$

Where COP_1 and COP_2 are, respectively, the performance coefficients of the two stages and Q_i is the heat supplied by the high temperature stage operating with zeolite to the low temperature stage operating with silica gel.

Calculation sequence

The equations of the mathematical model were discretized using the finite difference method with an explicit scheme for time-varying elements (the transient term). The equations governing the thermal behaviour of adsorbers were solved sequentially at each time step. The simulation code was developed using Matlab Simulink® and according to the sequence shown in Fig. 3. The results of the first step were used as inputs in the second step. The convergence relative criterion (Errc) used for energy equations was 2%.

This simulation tool allows for the simulation of the dynamic functioning of the cascading adsorption cycle. The temperature profiles in the various adsorbers constituting the cycle as well as the performance parameters of the cycle are established.

RESULTS AND DISCUSSIONS

The computational code developed was first validated using the results reported by Liu and Leong [14]. Then, the temperature and mass profiles of the three adsorbers were analysed at the nominal workingù temperatures considered for the cascading adsorption cycle. Finally, a parametric study concerning the effect of the three temperature levels (generation, condensation and evaporation) on the cycle performance parameters was carried out.

Verification of the mathematical model

The verification of the mathematical model developed to simulate the cascading adsorption refrigeration cycle was performed by comparing the simulation results with those published by Liu and Leong [14]. The input data used are summarized in table 2. It is worthy of note that in this case the working pairs were silica-gel/water and zeolite/water.

Figures 4 and 5 show the temperature and heat duty profiles in the three adsorbers of the adsorption cycle obtained in the present work and those of reference [14]. A good qualitative and quantitative agreement was observed between the two sets of data. The maximum relative error was about 0.3% for temperatures and 6.2% for heat duties (Table 3).

The mathematical model was then modified to include the expressions and values of the characteristic parameters of the working pairs used in the present work, namely activated carbon/ammonia and zeolite/ammonia. Some geometric data and working fluid characteristics reported by Vasiliev et al. [2] and Tamainot-Telto et al. [23] were used in the model.

Analysis of temperature and mass profiles in the three adsorbers

The variations versus time of temperature and adsorbed mass in the cascading adsorption cycle during the first two stages of the cycle are illustrated in Figures 6 and 7. Fig. 6 shows the temperature variation in the three adsorbers for the adsorption-evaporation and desorption-condensation phases of the adsorption cycle. These curves had similar trends during the adsorption phase where a continuous decrease in temperature towards the ambient asymptotic value was

observed for the activated carbon. During the desorption phase, temperature variations were in the opposite direction to the previous one.

Fig. 7 shows the variations versus time of the mass of ammonia adsorbed in the three adsorbers. These curves also followed similar trends during the desorption phase, where a rather rapid decrease was observed up to the end of this phase. The profiles showed a reverse variation during the adsorption phase for each adsorber. The circulating mass of ammonia in the zeolite zone of the cycle was $\Delta m_1 = 0.04$ kg$_{NH3}$.kg$_z^{-1}$ appearing to be well in agreement with the experimental data reported in the literature [2]. In addition, the mass of ammonia in circulation in the cycle zone working with activated carbon was $\Delta m_2 = 0.18$ kg$_{NH3}$.kg$_{ch}^{-1}$.

At the nominal thermal conditions of the cascading adsorption cycle, i.e. generation with zeolite (T_{gz}) at 280 ºC, generation with activated carbon (T_{gch}) at 110 ºC, condensation (T_c) at 35 ºC and evaporation (T_{ev}) at -5 ºC, the coefficient of performance (COP) and specific cooling capacity were in the order of 0.53 and 67.1 W.kg^{-1}, respectively.

Parametric study of the operation of the cascading adsorption cycle

The effect of heating, condensing and evaporating temperatures on the performance parameters (COP and SCP) of the cascading adsorption cycle are analysed in the following sections. These three thermal levels of the cycle were varied as follow: generation (260 ºC – 320 ºC), condensing (25 ºC – 50 ºC) and evaporating (-15 ºC – 5ºC). The variation interval of the heat source temperature was wider than the two other intervals.

Effect of heating temperature

Fig. 8 shows the variation of the coefficient of performance (COP) and the specific cooling capacity (SCP) by varying the inlet temperature (T_{hin}) of the external heating fluid between 260 ºC and 320 ºC. Evaporating and condensing temperatures were kept constant at -5 ºC and 35 ºC, respectively. A significant effect of the heating temperature variation on the adsorption cycle performance was observed. When the driving temperature was varied from

260 ºC to 320 ºC, the COP increased by about 57%, but this increase was less pronounced in the high temperature zone until a limit value at T_{hin}=310 °C was reached. This was because, above this limit temperature, the energy used to heat the adsorbers only served to increase the sensitive heat.

As regards the specific cooling capacity, its variation was more linear, increasing from 54.7 to 73.5 W.kg^{-1} when the driving temperature was varied from 260 ºC to 320 ºC. This represented an increase of about 36%.

Effect of condensing temperature

The increase of the condensing temperature implies that the condensing pressure increases, leading to an increase of the regeneration temperature at the end of the desorption-condensation phase which in turn leads to a decrease of the ammonia mass in circulation and consequently, a decrease of the quantity of cold produced. Fig. 9 shows the effect of condensing temperature on the coefficient of performance (COP) and specific cooling capacity (SCP) at heating and evaporating temperatures of 280 ºC and -5 ºC, respectively. The effect of the condensing temperature on the performance parameters of the cascading adsorption cycle was very pronounced. By increasing the condensing temperature from 30 to 40 ºC, the COP and SCP were reduced by about 25% and 26%, respectively. At a condensing temperature of 50 ºC, typical for operating conditions in warm climates, the COP and SCP were in the order of 0.30 and 37.5 W.kg^{-1}, respectively.

Effect of evaporating temperature

The performance parameters of the cascading adsorption refrigeration cycle increased with the evaporating temperature (Fig. 10). This was because the increase in the mass of ammonia in circulation increased the cooling capacity.

It is worth mentioning that when the cascading adsorption cycle investigated in the present work was operated under the working conditions used by Liu and Leong [14], i.e. for

cooling applications (T_{ev}=5 ºC), the coefficient of performance was reduced to almost half (0.64 versus 1.35). However, the specific cooling capacity was much higher (83 versus 43 W.kg^{-1}). In addition, at an evaporating temperature of -15 ºC the adsorption cycle had a COP of 0.43 and a PCS of 54.5 W.kg^{-1}. This demonstrates the great potential of this configuration of the adsorption cycle in combination with the working pairs proposed in this work for applications requiring low temperature cooling.

At the nominal thermal conditions considered in the present work, namely heating, condensing and evaporating temperatures of 280 ºC, 35 ºC and -5 ºC, respectively, the coefficient of performance (COP) and the specific refrigerating capacity (SCP) of the cycle were of the order of 0.53 and 67.1 W.kg^{-1}. The evaporation and condensation pressures at these nominal temperatures are 3.5 and 13.4 bar, respectively.

CONCLUSIONS

A cascading adsorption cycle was analyzed in this work for applications requiring low temperature cooling and using high temperature heat sources. The working pair selected for each of the two cycles forming the cascading cycle was activated carbon/ammonia for the cycle operating at low temperatures and zeolite/ammonia for the cycle operating at high temperatures. This configuration of the adsorption cycle would mean that the great potential of solar energy available in arid and semi-arid areas could be used to great advantage. Many of these areas are not connected to the electricity grid or do not have a continuous supply of electrical energy for the conservation and preservation of food, vaccines and pharmaceutical products and for ice making. The nominal temperatures considered for the operation of the cycle were: generation with zeolite (T_{gz}) at 280 ºC, generation with activated carbon (T_{gch}) at 110 ºC, condensation (T_c) at 35 ºC and evaporation (T_{ev}) at -5 ºC. The main results are summarized below.

- The mathematical model describing the functioning of the cascading adsorption cycle was validated using the data reported by Liu and Leong [14]. A good agreement between the

two sets of data was observed. The maximum relative deviation was about 0.3% for temperatures and 6.2% for heat duties.

- At the nominal thermal conditions defined above, the coefficient of performance (COP) and specific cooling capacity (SCP) of the cycle were in the order of 0.53 and 67.1 W.kg^{-1}, respectively.

- The effect of heating, condensing and evaporating temperatures on the performance parameters (COP and SCP) of the cascading adsorption cycle was analysed under the following conditions: generation (260 ºC – 320 ºC), condensation (25 ºC – 50 ºC) and evaporation (-15 ºC – 5 ºC).

- A significant effect of the heating temperature on the performance parameters of the adsorption cycle was observed. When the driving temperature was varied from 260 ºC to 320 ºC, the COP increased by 57% and the SCP by 36%.

- The effect of the condensing temperature on the performance parameters of the cascading adsorption cycle was very pronounced. At a condensing temperature of 50 ºC, typical for operating conditions in warm climates, the COP and SCP were in the order of 0.30 and 37.5 W.kg^{-1}, respectively.

- The performance of the cascading adsorption cycle at negative evaporating temperatures was very satisfactory. At an evaporating temperature of -15 ºC, the COP and SCP were in the order of 0.43 and 54.5 W.kg^{-1}, respectively. This demonstrates the great potential of this configuration of the adsorption cycle in combination with the working pairs proposed in this work for applications requiring low temperature cooling.

ACKNOWLEDGEMENT

NOMENCLATURE

Cp: specific heat, J.kg^{-1}.K^{-1}

L_v: latent heat of vaporization, J.kg^{-1}

ΔH: heat of adsorption of zeolite/ammonia, J.kg^{-1}

$\Delta H'$: heat of adsorption of activated carbon/ammonia, J.kg^{-1}

M: weight, kg

$\dot{m}_f$: mass flow rate of the heat transfer medium, kg.s^{-1}

P: pressure, Pa

T: temperature, K

t: time, s

x: adsorption rate, kg.kg^{-1}

COP: coefficient of performance in cooling mode

SCP: specific cooling capacity, W.kg^{-1}

NTU_i: number of heat transfer units of adsorber i (i=1, 2 or 3), [-]

Q_f: heat flow exchanged between heating medium and adsorber, W

Indices

ads: adsorbent

z: zeolite

ch: activated carbon

a: ammonia

a1, a2: adsorbers 1 and 2 working with zeolite

a3: adsorber 3 working with activated carbon

f: fluid

ev: evaporating

c: condensing

in: input

out: output

HXF: Heat Exchange Fluid

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Table Caption List

Table 1: Coefficients of the D-R equation for the activated carbon/ammonia working pair [23]

Table 2: Input data used in the verification of the mathematical model

Table 3: Maximum relative deviations in the three adsorbers

Fig. Caption List

Fig. 1: Diagram showing the cascading adsorption refrigeration cycle

Fig. 2: Representation of the theoretical cascading adsorption cycle in the Clapeyron diagram

Fig. 3: Calculation sequence used in the simulation code

Fig. 4: Temperature profiles in the three adsorbers: (a) present work; (b) Liu and Leong [14]

Fig. 5: Heat duty profiles in the three adsorbers: (a) present work; (b) Liu and Leong [14]

Fig. 6: Temperature variation versus time in the three adsorbers

Fig. 7: Mass of ammonia adsorbed versus time in the three adsorbers: (a) Adsorber 3; (b) Adsorbers 1 and 2

Fig. 8: Coefficient of performance (COP) and specific cooling capacity (SCP) of the cascading adsorption cycle as a function of the heating temperature

Fig. 9: Coefficient of performance (COP) and specific cooling capacity (SCP) of the cascading adsorption cycle as a function of the condensing temperature

Fig. 10: Coefficient of performance (COP) and specific cooling capacity (SCP) of the cascading adsorption cycle as a function of the evaporating temperature

Table 1: Coefficients of the D-R equation for the activated carbon/ammonia working pair [23]

	x_0	K	n	ρ (kg.m^{-3})
KOH-AC	0.6245	4.613	1.0554	500

Table 2: Input data used in the verification of the mathematical model

Parameter	Value	Parameter	Value
$\dot{m}_f$	1 kg.s^{-1}	C_{pc}	920 J.kg^{-1}.K^{-1}
m_c	1 kg	C_{pz}	836 J.kg^{-1}.K^{-1}
m_z	1 kg	C_{pf}	2090 J.kg^{-1}.K^{-1}
NTU_1, NTU_2, NTU_3	0.004	C_{pa}	4900 J.kg^{-1}.K^{-1}
ΔH	4×10^6 J.kg^{-1}	$\Delta H'$	1.5×10^6 J.kg^{-1}
L_0, L_1	4372, -31.17	L_2, L_3	0.12, 4.317 10^{-4}

Table 3: Maximum relative deviations in the three adsorbers

	Ads 1	Ads 2	Ads 3
Maximum relative error of temperature (%)	0.8	0.7	1.6
Maximum relative error of heat duty (%)	7.5	1.3	9.8
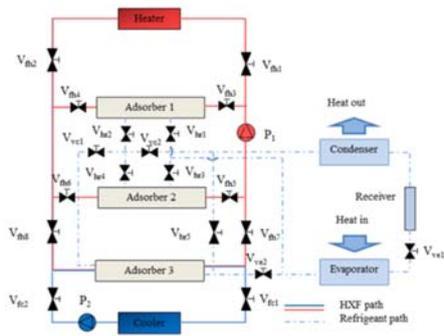
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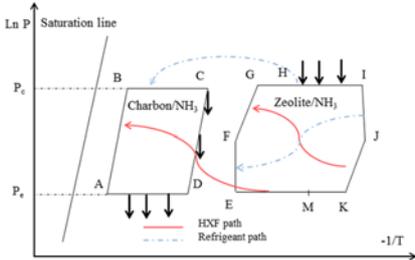
Figure 2: Representation of the theoretical cascading adsorption cycle in the Clapeyron

diagram
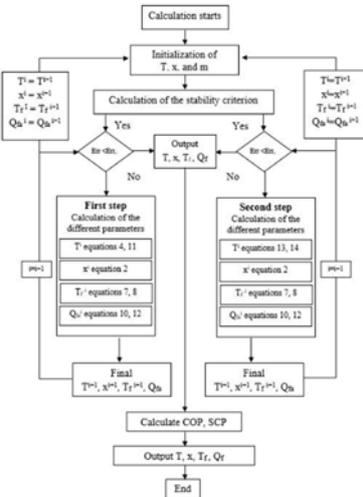
Figure 3: Calculation sequence used in the simulation code
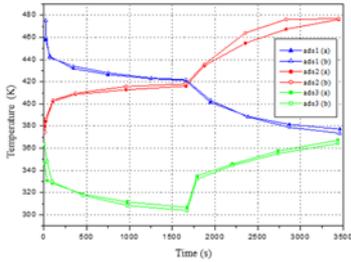
Figure 4: Temperature profiles in the three adsorbers: (a) present work; (b) Liu and Leong [14]
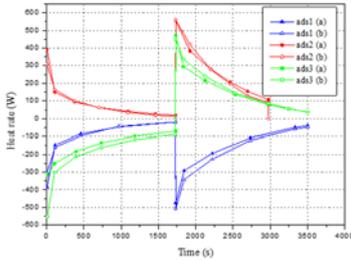
Figure 5: Heat duty profiles in the three adsorbers: (a) present work; (b) Liu and Leong [14]
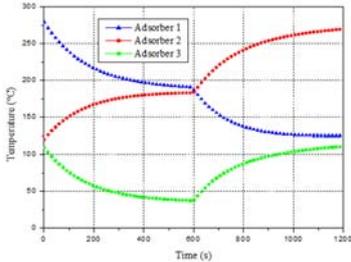
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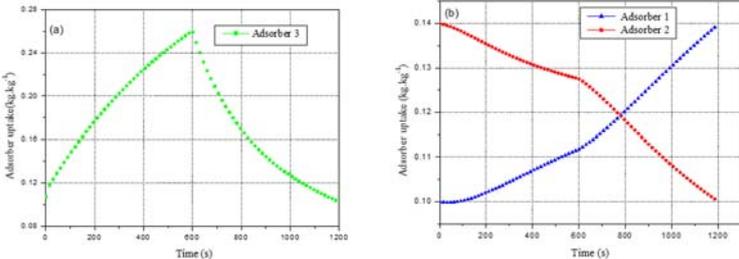
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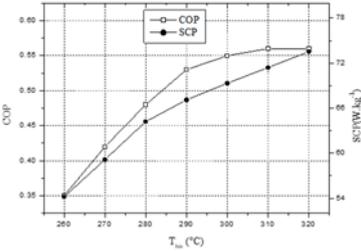
Figure 8: Coefficient of performance (COP) and specific cooling capacity (SCP) of the

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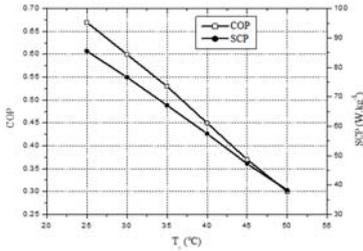
Figure 9: Coefficient of performance (COP) and specific cooling capacity (SCP) of the

cascading adsorption cycle as a function of the condensing temperature
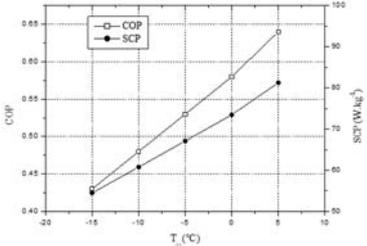
Figure 10: Coefficient of performance (COP) and specific cooling capacity (SCP) of the

cascading adsorption cycle as a function of the evaporating temperature