Central air conditioning based on adsorption and solar energy

Antonio Pralon Ferreira Leite [a], Francisco Antonio Belo [b], Moacir Machado Martins [c], Douglas Bressan Riffel [d],*

[a] Federal University of ABC, Brazil
[b] Solar Energy Laboratory, Federal University of Paraiba, 58051-900, João Pessoa, PB, Brazil
[c] Federal Institute of Pernambuco, Av. Professor Luis Freire, 500, Cidade Universitária, 50.740-540, Recife-PE, Brazil
[d] Department of Mechanical Engineering, Federal University of Sergipe – UFS, Av. Marechal Rondon S/N, 49100-000 Aracaju-SE, Brazil

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ABSTRACT

This paper presents the characterization and the pre-dimensioning of an adsorption chiller as part of a 20 kW air conditioning central unit for cooling a set of rooms that comprises an area of 110 m². The system is basically made up of a cold water storage tank supplied by an activated carbon–methanol adsorption chiller, a hot water storage tank, fed by solar energy and natural gas, and a fan-coil. During an acclimatization of 8 h (9–17 h), the following parameters were obtained for dimensioning the cooling system: 504 kg of activated carbon, 180 L of methanol, 7000 L of hot water, 10,300 L of cold water with its temperature varying in the fan-coil from 1 °C to 14 °C. Considering the mean value of the total daily irradiation in João Pessoa (7°8′S, 34°50′WG), and a cover of regenerating heat supplied by solar energy equivalent to 70%, the adsorption chiller's expected coefficient of performance (COP) was found to be around 0.6.

1. Introduction

Solar cooling is an interesting application of solar energy because, the stranger the insolation, the greater needs for cooling. As a rule, the systems requiring thermal energy as their main power input for the production of frigorific effect are most dependable on sorption processes. The use of solar energy for cooling applications – a device based on the liquid sorption cycle – was reported more than forty years ago by Chinnappa [1].

The energy needed for a sorption cooling system is essentially thermal, and may come from different sources, such as: process heat, residual vapor or solar energy. One of the main advantages of such a system in relation to the conventional vapor compression system lies on its minimum use of electric energy and on its low cost of maintenance.

Because of its functioning simplicity, the adsorption technology applicable to refrigerating systems differs significantly from that of absorption. In adsorption there occurs an interaction between a solid and a fluid – the transportation of the latter being a dependable thermal gradient, for it does not require the use of pumps. In the case of absorption, a solution interacts with a refrigerating fluid, calling for a number of electromechanical devices so as to move both the solution and the fluid.

Moreover, the adsorption cycle depends on fewer electromechanical components (heat exchangers, valves). Conversely, adsorption refrigeration has exhibited performance coefficients lower than those obtained by liquid absorption. In the field of solar refrigeration by adsorption, various kinds of solid pairs have been considered; zeolite–water [2,3] and silica gel–water [4,5] are used for cold storage, whereas activated carbon–methanol [6,7] and activated carbon–ammonia [8,9] are used for ice production.

A comparative study between the liquid, chemical reaction and adsorption cooling systems was published by Meunier [10]. In all these systems, the mechanical energy consumption is kept to a minimum or null. This represents a great advantage over the conventional vapor compression systems, especially in countries like Brazil whose energy consumption depends heavily on hydroelectric power.

Solar energy is abundant over large areas in Northeastern Brazil (annual average being over 6 kW/m² day), securing, as a result, a great potential supply for use in helio-thermal conversion systems applicable for both heating and cooling purposes. Many farm and fishing products are lost in this region, mainly because of unsatisfactory refrigeration, or otherwise, these products have their final value decreased for lack of economical frigorific preservation.

In the last two decades, absorption chillers, running on natural gas, have been introduced in markets all over the developed world

* Corresponding author.
E-mail address: dougbr@ufs.br (D.B. Riffel).

− in the US, Japan, France, Italy, Spain and more recently in Portugal. As to adsorption systems − in spite of several studies that demonstrate their technical feasibilities −, there exist only experimental units, though stand considerable chances of becoming economically viable, especially where thermal comfort applications are concerned [11].

This paper presents some of the adsorption fundamentals and also the energy equations for adsorbers. Then it puts forwards the characterization and the pre-dimensioning of a 20 kW air conditioning unit based on both the adsorption process and solar energy. Cold water is produced during night-time in an activated carbon−methanol adsorption chiller and then stored into a tank in order to supply cooling air during day-time. Solar energy is used for regenerating the adsorbent medium by means of highly efficient flat-plate collectors. Thermal energy is stored in a hot-water tank so as to feed the chiller at night. The central unit was created to provide thermal comfort to four adjoined laboratory rooms, whose total area is 110 m^2.

2. Adsorption fundamentals

Adsorption constitutes a solid sorption process by which the binding forces between fluid molecules (adsorbate) and the solid medium (adsorbent) derive from an electrostatic origin or from dispersion−repulsion forces. It is an exothermic process as a result of the gas−liquid phase change. The energy liberated during adsorption is called *isosteric heat,* and it depends on the nature of the adsorbent−adsorbate pair.

A number of state equations − known as *isotherms of adsorption* − are proposed. These functions correlate the temperature T, the pressure P, and the concentration of the adsorbed phase a, so that $f(T, P, a) = 0$. The main isotherms of adsorption are: (a) Henry's law, valid only for weak concentrations; (b) Langmuir's approach, which takes up adsorption on monomolecular layers where there is a dynamic equilibrium between the phases; (c) Gibbs' theory, which is based on the perfect gas equation, where the adsorbate is treated as a microscopic and bi-dimensional form; and (d) Eucken and Polany's theory, the so-called *potential adsorption theory,* in which it is assumed that within the space around each solid, it is possible to find some isopotential surfaces restricting the adsorbate that is adsorbed at pressures (or concentrations) lower than those corresponding to the potential value, being such isopotential surfaces specific for a given solid surface [12].

Dubinin and Radushkevich have proposed the *micropore volume filling theory*, which is related to Eucken-Polanyi potential theory. The Dubinin−Rudushkevich isotherm describes adsorption as a single type of uniform pores that is similar to Langmuir-like local isotherms in adsorption on energetically heterogeneous solids. This theory was later expanded by Stoeckli, allowing it to describe adsorption on energetically heterogeneous solids with a continuous distribution of pore sizes. Leite [13] puts forward a detailed analysis of the thermodynamics of adsorption and its different isotherms.

In general, all microporous materials are adsorbent and are characterized by their high porosity. Their structures have pores with diameters smaller than 20 Å. The most common absorbents are silica gel, activated carbon, zeolite and alumines. Zeolite−water and activated carbon−methanol are one of the most adsorbent−adsorbate pairs utilized in refrigeration systems. Methanol is easily desorbed from activated carbon when heated, whereas in zeolite, the water is sustained for much longer. Thus, the activated-methanol pair is best adapted for operating cycles with small evaporating temperature variations (up to 40 °C), whereas the adsorption cycles with zeolite−water pair, a larger range evaporating temperature (70 °C, or more) is needed.

2.1. Dubinin−Astakhov equation

To describe adsorption in microporous materials with poly-modal distributions, Dubinin and Astakhov [14] have proposed an isotherm that is a log-linear form of Dubinin−Rudishkevich equation, which can be expressed as follows:

$$a = W_o\rho_l(T)\exp\{-D[T\ln(P_s/P)]^n\} \tag{1}$$

where a is the concentration (adsorbed mass per unit of adsorbent mass), W_o is the maximum adsorption capacity (volume of adsorbate/mass of adsorbent), ρ_l is the specific mass of the liquid adsorbate, D is the "coefficient of affinity" and n is a characteristic parameter that depends on the adsorbent−adsorbate pair.

This equation has a wide field of application, and it is particularly suitable for strongly activated carbon with high pores heterogeneousness. According to Passos [15], for regenerating temperature ranging from 20 to 100 °C, and for concentrations, raging from 71 to 286 g/kg of adsorbent, a fitted curve, obtained from methanol adsorption experimental data, showed a residual error of 2.2%. These results demonstrate that this state equation is most suitable for a number of engineering applications of low-grade sources, especially those concerning solar energy.

2.2. Isosteric heat of adsorption

The energy released during the adsorption process, i.e. the isosteric heat (Q_{st}) can be derived from the Gibbs' isotherm, being reduced to a constant adsorbed mass function called *isoster*, which is given as follows

$$\left(\frac{\partial\ln P}{\partial T}\right)_a = -\frac{q_{st}}{RT^2} \tag{2}$$

For the saturating condition ($P = P_s$), the q_{st} term in Eq. (2) is replaced by the latent heat L. Then,

$$L = -RT^2\left(\frac{\partial\ln P_s}{\partial T}\right)_a \tag{3}$$

The Dubinin−Astakhov equation becomes

$$\frac{\partial\ln P}{\partial T} = \frac{\partial\ln P_s}{\partial T} + \ln(P_s/P)\left\{T^{-1} + \frac{\alpha}{nD}[T\ln(P_s/P)]^{-n}\right\} \tag{4}$$

with

$$\alpha = W_o\frac{\partial\ln(\rho_l/a)}{\partial T} \tag{5}$$

where α is the coefficient of thermal expansion of the liquid adsorbate. Integrating Eq. (4) and, after some algebraic operations, the isosteric heat of adsorption can be given as

$$q_{st} = L + RT\ln(P_s/P) + \left[\frac{\alpha RT}{nD}\right][T\ln(P_s/P)]^{(1-n)} \tag{6}$$

Being the latent heat, the first term of Eq. (6), the other terms do correspond to the energy that most specifically concerns the adsorption binding forces. For temperature around −5 °C, the value of L is about 1200 kJ/kg. According to Srivastava and Eames [16], the isosteric heat of adsorption for activated carbon−methanol ranges from 1800 to 2000 kJ/kg. So, the energy resulting from the binding forces in adsorption corresponds to something from 33% to 40% of the isosteric heat; the rest would come as a result of capillary condensation inside the micropores.