ICREN-01/2013 February 16-17, 2013 Constantine, Algeria
First International Conference on Renewable Energies and Nanotechnology impact on Medicine and Ecology

Thermodynamic Study and Analysis of Heat Recovery Adsorption Refrigeration Cycle

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Abstract

A detailed thermodynamic analysis of simple and regenerative cycles of adsorption refrigeration is presented. Two functions of the incoming and outgoing energy for the regenerative cycle using two isothermal adsorbers have been calculated, in order to obtain the heated adsorber temperature at the end of heat recovery. Results are presented in terms of performances for the pair activated carbon AC-35 as adsorbent and methanol as adsorbate. These results demonstrated that the performance coefficient of double bed adsorption refrigeration cycle increases with respect to the single bed configuration. Several main factors affecting the performances of cycles are discussed according to the results of computer simulations.

Keywords: Adsorption system; heat regenerative; performance; thermodynamics.

1. Introduction

Adsorption refrigeration is a technology of environmental friendly refrigeration, which can be driven by solar energy or waste heat. In recent years, adsorption refrigeration has already been widely studied. With the development of its technologies and theories [1-5], the application of adsorption refrigeration is getting extensive, research indicates that adsorption is friendlier for environment than HFC vapor compression in several cases, such as waste heat powered adsorption cycle [5], natural gas fired air conditioning [6], reversible heat pump [7], cold stores for transportation [1] etc.

However, the basic cycle of adsorption refrigerating machines presents two main draw backs: the production of cold is intermittent and the efficiency is low. To attain higher efficiencies and to achieve continuous production of cold, it is necessary to use advanced cycles. Several kinds of advanced cycles have been proposed and tested. Two main technologies have been developed: regenerative processes with uniform temperature adsorbers and regenerative processes with temperature fronts (or thermal waves).

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Nomenclature

COP_s , COP_d	performance coefficient in single bed and double bed, respectively
Cp_{ml} , Cp_{mg}	Specific heat of the adsorbate in liquid and vapour state, respectively , J/kg k
Cp_a , Cp_g	Specific heat of the adsorbent, and the metal of the adsorber, respectively, J/kg k
L	Latent heat of evaporation, KJ/kg
m , m_a , m_g	Adsorbed mass, mass of the adsorbent and metallic mass of the adsorber, respectively, kg
$m_{\max}$, $m_{\min}$	Adsorption mass at adsorbed and desorbed state respectively, kg/kg
T_a , T_g	Adsorption and regenerating temperature, respectively,°C
T_{c1} , T_{c2}	Limit temperature of desorption and adsorption, respectively, °C
T_r	Heated adsorber temperature at the end of heat recovery,°C
T_e , T_c	Evaporation and condensation temperature, respectively, °C
Q_f , Q_c	Cooling power and Total heat necessary for heating the adsorber, respectively, KJ/kg
Q_r	Heat recovered, KJ/kg
q_{st}	Isosteric heat of adsorption, KJ/kg
r	Heat recovery ratio
ΔT_r	Two adsorber temperature difference at the end of heat recovery, °C

The basic idea is to use the heat discarded by one adsorber under cooling to pre-heat another adsorber under heating. In so doing, the COP is enhanced and the production of cold is continuous.

In this paper, we interest to the uniform temperature adsorbers. A numerical analysis was carried out, studying the influence of the main parameters on both of regeneration and performance coefficients of the machine. A detailed thermodynamic and parametric analysis of a double adsorptive cycle is given. The basic fundamentals of the adsorption process are discussed, where the Dubinin-Astakhov equation is used to describe the isotherm of adsorption.

2. System description

Adsorption refrigeration systems have been initially proposed of a single adsorbent bed alternately connected to a condenser and evaporator. Theoretically, the corresponding cycle consists of two isosters and two isobars, as illustrated in the Clapeyron diagram (Fig. 1). The process starts at point **a**, where the adsorbent is at a low temperature T_a and at low pressure P_e (evaporation pressure). While the adsorbent is heated, the temperature and the pressure increase along the isoster which the mass of the adsorbate in the adsorbent remains constant at $m_{\max}$. The adsorber still isolated until the pressure reaches the condenser pressure at point **b**. At this time, the adsorber is connected with the condenser and the progressive heating of the adsorbent from point **b** to **c** causes a desorption of methanol and its vapour is condensed in the condenser and collected in a receiver. When the adsorbent reached its maximum temperature value T_g (regenerating temperature)and the adsorbed mass decreases to its minimum value $m_{\min}$ (point c), the adsorbent starts cooling along the isoster at a constant mass $m_{\min}$ to point **d**. During this isosteric cooling phase, the adsorbent pressure decrease until it reaches the evaporator pressure P_e . After that, the adsorber is connected to the evaporator, and both adsorption and evaporation occur while the adsorbent is cooled from point **d** to **a**. In this phase, the adsorbed mass increases up to its maximum $m_{\max}$ at point **a** and the adsorbent is cooled until the adsorption temperature T_a. During this phase also, the cold is produced.

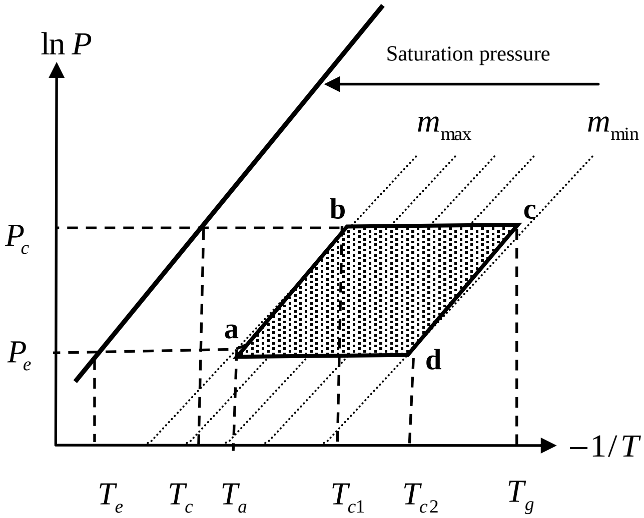

Fig. 1. Clapeyron diagram of a single bed adsorption cycle.

The discontinuity of the useful effect makers the system with single adsorber commercially unsuitable. Later, two adsorbent bed machines have been proposed [8,9], in order to operate regenerative cycles. By these both the results of a higher overall efficiency and a continuous useful energy production can be obtained. The idealized thermodynamic cycle of a double bed adsorption machine is plotted in Fig.2. The adsorbent beds operate the same cycle but in counter phase, so that the heat recovery is obtained by transferring the heat from one bed to the other, until a fixed difference of temperature ΔT_r between beds is reached.

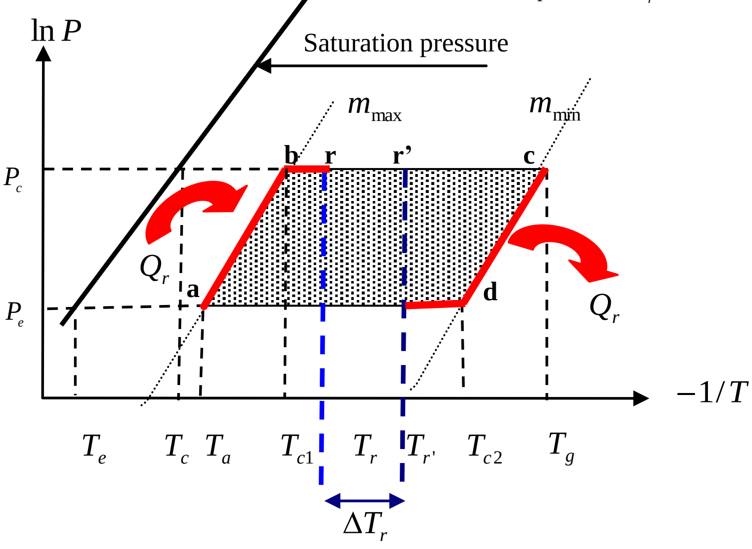

Fig. 2. Clapeyron diagram of a regenerative adsorption cycle.

3. Thermodynamic model

In the following, the developed model is described with reference to a single bed adsorption system (Fig.1) and the main difference introduced in modeling of a two bed system are also presented.
In order to calculate the coefficient of performance of the machine, all the thermal contributions must be calculated in detail; the most important equations used in the model are described below.
The heat that must be supplied to the adsorber for its heating is:

$$Q_c = Q_{ab} + Q_{bc} \qquad (1)$$

Where, Q_{ab} is the heat that must be supplied to the adsorber for its isosteric heating:

$$Q_{ab} = \int_{T_a}^{T_{c1}} \left[Cp_a + m_g Cp_g + m_{\max} Cp_{ml}(T) \right] m_a \, dT \qquad (2)$$

Q_{bc} is the heat needed for the desorption phase:

$$Q_{bc} = \int_{T_{c1}}^{T_g} \left[Cp_a + m_g Cp_g + m(T) Cp_{ml}(T) + q_{st} \frac{\partial m}{\partial T} \right] m_a \, dT \qquad (3)$$

During the isosteric cooling phase, only the sensible heat is withdrawn from the bed:

$$Q_{cd} = \int_{T_{c2}}^{T_g} \left[Cp_a + m_g Cp_g + m_{\min} Cp_{ml}(T) \right] m_a \, dT \qquad (4)$$

While during the adsorption phase, the energy released is equal to the heat of adsorption, plus the sensible heat obtained from cooling of adsorbent, adsorber and adsorbate, from critical adsorption temperature to adsorption temperature , minus the energy needed to heat up the vapor from evaporation to adsorption temperature.

$$Q_{da} = \int_{T_a}^{T_{c2}} \left[Cp_a + m_g Cp_g + m(T) Cp_{ml}(T) + q_{st} \frac{\partial m}{\partial T} - (T - T_e) Cp_{mg}(T) \frac{\partial m}{\partial T} \right] m_a \, dT \qquad (5)$$

The energy at must be supplied to the evaporator Q_f, is calculated as the latent heat of evaporation of the cycled adsorbate, minus the sensible heat of the adsorbate that entering the evaporator at condensation temperature:

$$Q_f = m_a\,(m_{\max} - m_{\min})\left[L(T_e) - \int_{T_e}^{T_c} Cp_{ml}(T)\,dT\right] \tag{6}$$

The adsorbed mass is obtained from the state equation of the bivariant solid-vapour equilibrium using Dubinin- Astakhov model.

On the basis of the previous equations, the coefficient of performance of single adsorbent bed, can be calculated as the ratio of useful effect produced and energy supplied to the machine:

$$COP_s = \frac{Q_f}{Q_c} = \frac{Q_f}{Q_{ab} + Q_{bc}} \tag{7}$$

In the regenerative cycle the above parameters have been calculated between $m_{\max}$ and a generic isosteric line $m_r \geq m_{\min}$; the function Q_{ar} is calculated in order to obtain the energy incoming to the system when its temperature increase from T_a to a generic value T_r . The thermodynamic cycle of the heat regenerative adsorption cycle can be expressed by Fig.2. The function Q_{ar} can be represented by the following expression, for $T_{c1} \prec T_r \prec T_{c2}$:

$$Q_{ar} = Q_{ab} + \int_{T_{c1}}^{T_r}\left[Cp_a + m_g Cp_g + m(T)Cp_{ml}(T) + q_{st}\,\frac{\partial m}{\partial T}\right] m_a\,dT \tag{8}$$

In the same way the function $Q_{cr'}$ has been calculated. It represents the energy out coming from the system when its temperature decrease from T_g to a generic value $T_{r'}$ where $T_{r'} = T_r + \Delta T_r$; ΔT_r is the two adsorber temperature difference at end of heat recovery. The temperature at which Q_{ar} is equal to the absolute value of $Q_{cr'}$ is the final temperature of the regenerative phase T_r , and the corresponding value of the function Q_{ar} or $Q_{cr'}$ is the regenerative energy Q_r . In this case, the performance of the machine can be calculated by he following formulae:

$$COP_d = \frac{COP_s}{1 - r} \tag{9}$$

Where, r is the coefficient of regeneration (or the heat recovery ratio)), it can be calculated by:

$$r = \frac{Q_r}{Q_{ab} + Q_{bc}} \tag{10}$$

4. Results

We admit the following data: the pair activated carbon AC-35/methanol as an adsorptive pair, this last has proved to be the best pair among those studied; the copper is a material of construction of the adsorber; $m_g = 5kg$ its mass; $m_a = 1\,kg$ is an adsorbent mass; two adsorber temperature difference at the end of heat recovery $\Delta T_r = 2\,°C$; adsorption temperature $T_a = 25\,°C$, condensation temperature $T_c = 30\,°C$;

evaporation temperature $T_e = 0\,°C$ and regenerating temperature $T_g = 105°C$. The performances under this conditions is predicted as: $COP_d = 0.682$; $COP_s = 0.483$ and $r = 0.291$($r = 29.1\%$). The influence of the regenerating temperature on performance coefficients, heat recovery ratio and temperature at the end of heat recovery is shown in Figs. 3, 4 and 4, respectively.

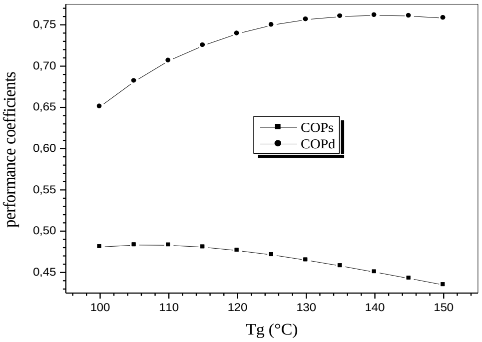

Fig. 3. Influence of regenerating temperature T_g on performance coefficients COP_s and COP_d .

From Fig.3, with the increase of regenerating temperature, COP_d increase all along, while, COP_s decrease from regenerating temperature $T_g = 105°C$. This behaviour can be justified by the fact that after certain regenerating temperature, the energy of heating only serves to increase the activated carbon temperature, the adsorber metal parts temperature and the methanol temperature, nevertheless the desorbed mass of methanol $m_{\min}$ becomes more and more weak. Where, the heat provided to the adsorber Q_c increases more than the quantity of cold produced at evaporator level Q_f. It is clear that, in the case of two adsorbers, the performance of the system increases in an appreciable manner compared to the case of one adsorber.

The regenerating temperature is a design variable that must be optimized. Generally, it is stipulated to obtain a large amount of cycled masses at lower levels of T_g. In the case of the adsorption of methanol in activated carbon AC-35, this temperature is limited by 150 °C, because the methanol would decompose, the process of adsorption is blocked and the adsorption power of activated carbon decreases sharply beyond above mentioned temperature.

The heat recovery ratio r and the temperature at the end of heat recovery T_r, increase with the increase of T_g. (Fig. 4 and 5).

The influence of the adsorber mass on the performance coefficients of system COP_s and COP_d has been evaluated, by varying the mass m_g .

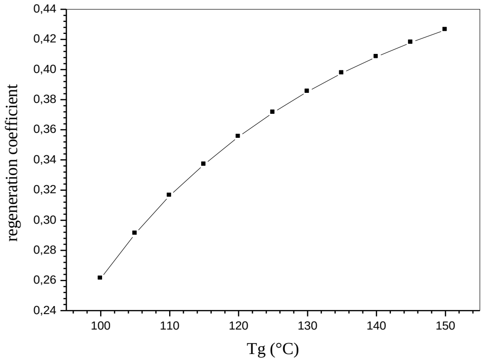

Fig. 4. Influence of regenerating temperature T_g on heat recovery ratio r .

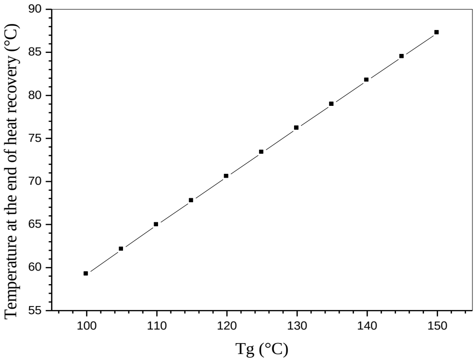

Fig. 5. Influence of regenerating temperature T_g on temperature at the end of heat recovery T_r .

From Fig. 6, if the adsorber metal mass increases, COP_s and COP_d reduce. The reason is that the bigger the heat capacity of the non-adsorbent materials is, the more the heat will be consumed for inert materials. Thus, a part of heating power becomes energy loss due to the switch between two adsorbers. This kind of energy loss leads to the decrease of performance coefficients of system COP_s and COP_d .

On contrary, the heat recovery ratio r and the temperature at the end of heat recovery T_r , are on the increase.

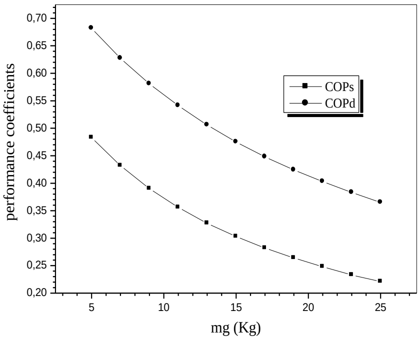

Fig. 6. Influence of adsorber mass m_g on performance coefficients COP_s and COP_d .

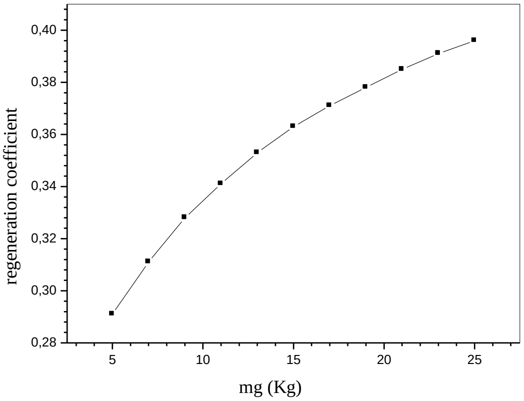

Fig. 7. Influence of adsorber mass m_g on heat recovery ratio

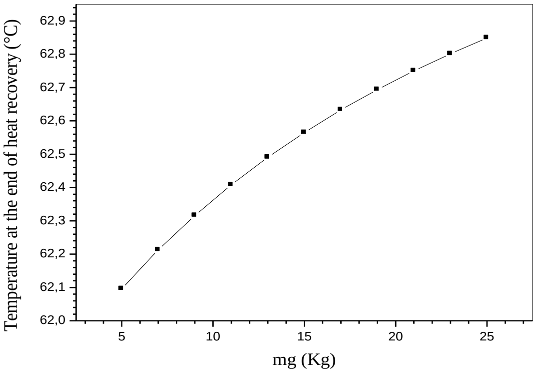

Fig. 8. Influence of adsorber mass m_g on temperature at the end of heat recovery T_r .

r .

5. Conclusions

A detailed thermodynamic model has been developed for the analysis of solid adsorption refrigeration system (single bed and two beds), using the pair activated carbon AC-35/methanol as an adsorptive pair. This model was usually expressed in algebric or relatively simple equations based on the representation of Dubinin-Astakhov.

The developed model is described with refrence to a single bed adsorption system and the main differences introduced in modelling of a two bed system are also presented.

By the computer program based on this model, it is possible to calculate the operative conditions and coefficient of performance and heat regenerative ratio.

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