

Physical kinetic study for adsorption of ethanol and acetone in activated carbon

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Abstract

The adsorption of a gas in a microporous solid is a matter of transfer with a movement quantity from one environment to another. This property is probably a transport phenomenon. In this case, the best mathematical model used to describe it is Fick's law. We propose a new theoretical expression of simulation of a gas in a microporous solid in order to find a better correlation with the experimental. In this paper, we underscore the importance of the physical kinetics of gas adsorption by a microporous solid. Using a good choice of pairs, we have determined the minimal distance from which the interaction forces adsorbate-adsorbent orients the adsorbate molecule to the adsorbent as well as the existence of a critical temperature and its effect on the relaxation time relative to the adsorbed matter quantity.

KEY WORDS: Kinetic, adsorption, diffusion, microporous solid

1. Introduction

Adsorption kinetics describes the rate of the adsorbate uptake governing the contact time of the adsorption reaction, which is an important characteristic defining the efficiency of adsorption [1]. Adsorption kinetics is also crucial to provide a good understanding of the adsorption mechanism. The adsorption kinetics study is gaining more and more importance as it interests many domains such as sorption, chemistry, bio-sorption, agro-chemistry, pharmaco-chemistry, the environment applications, security and the molecule separation [1]. The technologies dealing with complex transfers of heat, mass and movement quantity are developing in many industrial areas such as environment or security. The couplings of these transfer phenomena are often badly controlled and they need to be analyzed in an analytical and an experimental way. To determine the parameter which controls these coupled transfers, the adsorption kinetics of a gas by a microporous solid is of a great interest. [2, 3]. The adsorption of a gas in a microporous solid is the result of a phenomenon of the external transport and diffusion. The transport of gas in microporous materials is controlled by activated diffusion. It is essentially influenced by adsorption features, the geometry of the adsorbed molecule and the

micropore structure. [4]. Some studies assume that the adsorption is a diffusion phenomenon which happens in an isotropic and homogenous media, and therefore, they use Fick's law [5, 6, and 7]. Others underscore the effect of interaction forces such as forces of Van Der Waals, on the adsorption speed. Fowkes [8] and Habgood [9] have shown that the interaction molar energy increases with the adsorbate mass contained in this media, which induces heterogeneity of the interaction energy in this media.

Generally, the adsorption speed is controlled by the adsorbed mass and the resistance to the heat transfer instead of the adsorption intrinsic kinetics. There are many examples: mass and heat transfer of adsorbate to and from the exterior surface of the adsorbent (known as interparticle transport), Maxwellian diffusion (bulk molecular diffusion) in moderately large pores (macropores) or Knudsen diffusion in pores (micropores) which have a diameter smaller than the mean free path of the adsorbate molecules; intracrystalline diffusion within the channel and cage-like structure of molecular sieve materials such as zeolites and silicalites; surface diffusion when adsorbate molecules move freely over the internal surface of adsorbents in parallel with intraparticle diffusion; heat transfer within the interior of particles occasioned by the exothermic nature of adsorption. [10]. A direct measurement on an adsorbent sample enables to plot some curves yielding a simple method for the kinetic study. However, the interpretation of many data raises potentially insurmountable difficulties. In fact, there exist many different resistances to the transfer of mass and heat, which limits the adsorption speed. The influence of the thermal resistance on the kinetics has been studied by Valentina et al [11]. Since 1950, many theories of the adsorption kinetics have been developed. Some of them lead to equations which are difficult to apply as they imply many factors depending on the physico-chemical properties of the adsorbents and adsorbates [10]. Some others can be applied only by concentration intervals [12]. In the literature, we find empirical models whose parameters are not defined explicitly from a physical point of view [12, 13]. Moreover, in the proposed models, the number of constants experimentally determined is generally greater than three [14-15].

In order to facilitate the problem, some researchers have tried to give a linear form to the adsorption kinetic curves [16]. This idea, deduced from chemical kinetics, provides a good approximation only for the small intervals of the curve. From a microscopic point of view, the experiment shows that the adsorption of a gas in a microporous solid is due to the transportation and the diffusion, which introduces a supplementary complication in the study of the adsorption kinetics. In fact, from the study of the Brownian movement (Langevin equation) we show that both phenomena have different speeds. The adsorption kinetics approach from Fick's law needs the modification of the latter to take fluctuation into account [17]. Authors using Fick's law and neglecting the fluctuations and the difference between the transportation and the diffusion have been forced to define several diffusivities whose number may reach five [15]. A recent study [18] proposes a modification of Fick's law. This study doesn't propose any experimental approach. It also hides the heat and mass fluctuations. Due the complexity of the phenomenon, it is preferable to use Fick's diffusion [19, 20] despite these defects, which are corrected by the introduction of the fluctuation observed experimentally. In our study, we propose a new theory of the adsorption kinetics of a gas in a microporous solid. We start by a basic hypothesis such as the existence of diffusion; the direct adsorption and the existence of partial desorption. Then, we establish the differential equation from basic thesis hypotheses and we end by an analytical resolution of such an equation in an isotherm and isobar conditions, the solution contains only three constants to determine experimentally. However, in a non isotherm condition, the constant number is unchanged. Then, we proceed to model validation by its comparison with experimental values. The proposed model [21] is complicated from a mathematical point of view; its resolution has been

processed in a spherical coordinate system [21, 22, and 23] because of the spherical form of the microporous grains.

2. Experimental Study

Nomenclature

A: accumulation due to direct adsorption ($\text{mol kg}^{-1} \text{s}^{-1}$);

$\frac{1}{b}$: relaxation time relative to pressure in isobar condition (s);

D: diffusion constant of micro pores ($\text{m}^2 \text{s}^{-1}$);

f : proportionality constant;

i: Complex number $i^2 = -1$;

$n(r,t)$: average density of particles in point at time t (mol kg^{-1});

$n(r_c, t)$: Number of adsorbed molecules in (mol kg^{-1}) by spherical volume of r_c radius at time t;

$n_\infty = \lim_{t \rightarrow \infty} n(r_c, t)$ at 25°C , for this couple it is equal to 14.944 mol/kg (269 g/kg);

P: pressure (Pa), assumed to be constant;

r: instantaneous particle position in spherical coordinates (m);

r_c : radius of spherical grain of adsorbent (m);

t: time (s);

T: temperature ($^\circ\text{K}$);

$\frac{1}{\omega^2}$: relaxation time relative to temperature (s);

$\frac{1}{\omega_c^2}$: relaxation time relative to temperature T_c (s)

G0 : model flow of inert gas (mol s^{-1})

m : mass of adsorbed particles (kg mol^{-1});

M_{bed} : mass of active carbon bed (kg);

M : molar mass of solvent (g mol^{-1});

X_0 : the partial molar fraction of initial solvent in the air;

X: the partial molar fraction of solvent at time instant t in the air

N: number of adsorbed molecules by volume unit (mol m^{-3});

R^2 : coefficient of correlation;

Greek letters:

Δ : Laplatian operator;

α : integrate constant (m^{-1});

δ : integrate constant (m^{-2});

Index j^o

The measurements of the adsorbed mass are carried out in a fluidised bed in isotherm conditions. The used adsorbat is the active carbon PICANC60, the grain radius is between 0.3 and 0.6 mm; the bed mass is 0.3 kg; the bed height is 0.12 m and the reactor diameter is 100 mm. All the tests are performed with a solvent concentration at the input of 30 gm^{-3} (Fig 1). By considering the variation of the partial molar flow of the adsorbat between the column input and output equivalent to the adsorbed quantity per unit of time, we can write the following relation:

Input – output = accumulation

$$G_0 (X_0 - X) = M_{bed} \frac{dn}{dt}$$

with $X = \frac{x}{1-x}$ and $x = \frac{C_0}{M} \frac{RT}{P}$

We deduce n

$$n = \frac{X_0 G_0}{M_{lit}} \int_{t=0}^{t=t_f} \left(1 - \frac{X}{X_0}\right) dt$$

By integrating the previous equation, we obtain the value of n.

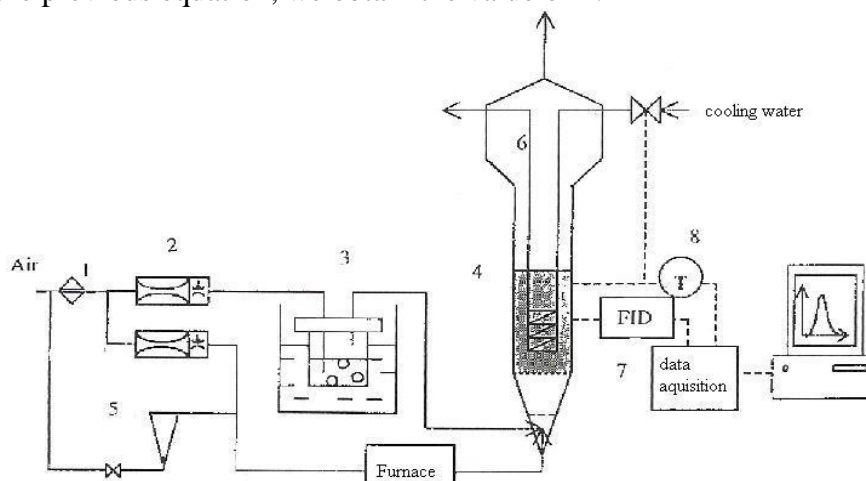


Fig 1 : Representative diagram of the installation utilized for the experimental tracing of isotherms.1: filter; 2: Mass volumetric governor; 3:Wash-bottle; 4: fluidized bed reactor; 5: Conical float rotameter; 6: Exchanger with cool water;7: Detector with ionization of flame; 8: Thermocouple.

3. Theoretical development

The intrinsic rate of physical adsorption is very rapid so the overall sorption rate is generally controlled by the diffusional associated mass transfer to the adsorption site [4]. Such materials offer at least three and in some cases four distinct mass transfer resistances. As a result of the imbalance of the interatomic forces, the micropores are often constricted at the crystal surface, leading to an additional transport resistance associated with penetration of this surface barrier.

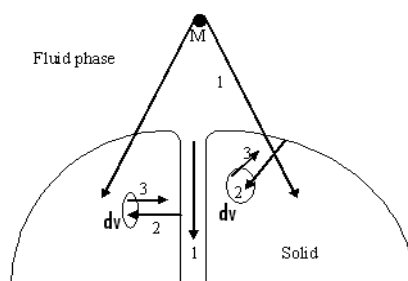


Fig 2: Transfer mechanism in microporous solids: 1: adsorption; 2: diffusion; 3: desorption

At the micropore scale, diffusive transport is largely controlled by steric interactions which are dominated by repulsive forces. The relative diameter of the micropore and the diffusing molecule is clearly a critical

variable. For small spherical or spheroidal molecules, there is a clear correlation between the diffusional activation energy and the kinetic diameter of the sorbate [24, 25]. Diffusion depends on the random (Brownian) motion of molecules. Because the motion is random, in a non uniform mixture of different molecular, the diffusion coefficient or (transport) diffusivity is defined in accordance with Fick's law. In a microscopic way, the adsorption process in elementary volume results from the succession of three phenomena which occur during the time: the direct adsorption of the exterior associated with the external surface to the adsorbent (transportation phenomenon), the matter diffusion inside the adsorbent and the exchange of the adsorbed matter do to fluctuation [26] as shown in Fig 2. The differential equation which describes the adsorbed quantity during the time results from a matter balance in an adsorbent elementary volume [26, 21]. The adsorbate accumulation is equal to the gain per diffusion inside the adsorbent plus the quantity directly adsorbed from outside plus the matter exchange due to fluctuation:

$$\frac{\partial n(r,t)}{\partial t} = D \Delta n(r,t) + A(r,t) + B(r,t) \quad (1)$$

In a spherical symmetry case and from [27], this equation is written as:

$$\frac{\partial n(r,t)}{\partial t} = D \Delta n(r,t) + b n(r,t) + Z(t)R(r) \quad (2)$$

Where $A(r,t) = b n(r,t)$ with b a constant in the isobar case as it depends only on the pressure and on the adsorbent's active surface [27, 21, 22]. Equation (2) has been solved using the variable separation method, the model chosen for $B(r,t)$ is $Z(t) R(r)$ where $Z(t)$ is the function which describes the deep link between the fluctuations and the dissipations of the matter and energy and $R(r)$ is the function that describes the matter distribution with respect to coordinates. The solution of equation (2) with the following limit conditions

$$n(r,0) = n_0 \quad ; n(r_c, \infty) = n_\infty \quad \text{and} \quad \left(\frac{\partial n}{\partial r} \right)_{r=0} = 0$$

To solve this equation, we do in the following way [28]: the method is used for the separation of variables: $n(r,t) = Y(t) R(r)$. These assumptions lead to solve the following equations system:

$$\frac{d^2 R(r)}{dr^2} + \frac{2}{r} \frac{dR(r)}{dr} + \alpha^2 R(r) = 0; r \in [0; r_c] \quad (3)$$

With α^2 is a strictly positive real

$$\frac{dY(t)}{dt} + \omega^2 Y(t) = Z(t) \quad (4)$$

With ω^2 is a positive real

The final equation can be written [22]:

$$n(r_c, t) = 4\pi Y(t) \sum_{j=1}^{\infty} 2^j \frac{(i\alpha)^j}{(j+1)!} e^{-i\alpha r_c} (j!)(j+1) \sum_{\gamma=0}^j \frac{(-2i\alpha)^{j-\gamma-1}}{\gamma! [(j-\gamma)!]^2 (j-\gamma+1)} [r_c^{j-\gamma+2} + \frac{j-\gamma+2}{i\alpha} r_c^{j-\gamma+1} + \frac{(j-\gamma+2)(j-\gamma+1)}{(i\alpha)^2} r_c^{j-\gamma} + \dots + \frac{(j-\gamma+2)!}{(i\alpha)^{j-\gamma+1}} r_c + \frac{2(j-\gamma+2)!}{(i\alpha)^{j-\gamma+2}}] \quad (5)$$

A first order development ($j = 1$), $Z(t) = C$ et $n(r,0) = 0$; equation (5) gives [22]:

$$\frac{n(r_c, t)}{n_\infty} = Y(t) \times \left[\left(r_c^2 + \frac{1}{\alpha^2} \right) \cos(\alpha r_c) + \left(\frac{\alpha}{2} r_c^3 - \frac{2}{\alpha} r_c \right) \sin(\alpha r_c) \right] i Y(t) \times \left[\left(\frac{\alpha}{2} r_c^3 - \frac{2}{\alpha} r_c \right) \cos(\alpha r_c) - \left(r_c^2 + \frac{1}{\alpha^2} \right) \sin(\alpha r_c) \right] \quad (6)$$

Where $Y(t)$ is given by [27]

$$Y(t) = \delta \left(1 - e^{-\frac{t}{\tau}}\right) (1 - e^{-\omega^2 t}) \quad (7)$$

α, ω^2 And δ characterize the adsorption phenomenon of a gas in a microporous solid. Where $1/\omega^2$ is the relaxation time relative to the temperature, measured in (s) and $1/\alpha$ is the minimum interaction distance measured in (m).

4. Fitting results

The theoretical study allowed us to find a mathematical expression which expresses the number of adsorbed molecules in a spherical volume of radius r_c with time, given by (Eq. (6)) and (Eq. (7)) where we consider the real part of equation and that $r_c = 0.45$ mm. The objective of the theoretical development is to give a physical meaning to the various terms that the model contains and thus facilitate the understanding of the adsorption process at the molecular scale. This theoretical study will enable us to better interpret and derive conclusions on the physical adsorption of the adsorbate / adsorbent. The choice of the appropriate model is based on the values of the adjustment coefficient R^2 corresponding to the model, and which is given by numerical simulation (origin 8: Data analysis and graphics software. Technical charts for scientists and engineers. 2D and 3D plotting, statistics, curve fitting, and peak fitting.). We note that the experimental curve shows a high correlation with the proposed model when the adjustment coefficient R^2 is close to 1 (Fig 3). In table 1 we present the characteristic parameters δ, α^2 and ω^2 .

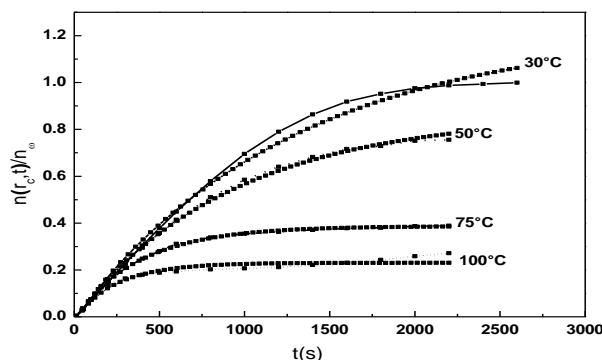


Fig 3: Evolution of relative quantity of ethanol adsorbed in activated carbon (----) theoretical curves (Eq. 6), (—) Experimental points

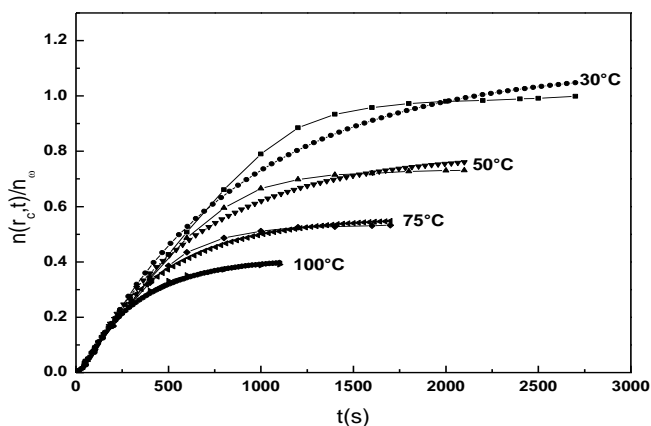


Fig 4: Evolution of relative quantity of acetone adsorbed in activated carbon (----) theoretical curves (Eq. 6), (—) Experimental points.

Table1. Fitting results

| Paire | T(°C) | ω^2 (s ⁻¹) | α (m ⁻¹) | τ (s) | δ (m ⁻²) | R ² |
|-----------------------|-------|-------------------------------|-----------------------------|------------|-----------------------------|----------------|
| Ethanol-active carbon | 30 | 0.0007 | 0.27 | 54.914 | 0.301 | 0.99697 |
| | 50 | 0.001 | 0.414 | 40.367 | 0.792 | 0.99892 |
| | 75 | 0.00253 | 0.861 | 39.966 | 0.933 | 0.99941 |
| | 100 | 0.00369 | 0.952 | 39.622 | 1.078 | 0.99081 |
| Acetone-active carbon | 30 | 0.0011 | 0.6262 | 145.37 | 0.3948 | 0.99629 |
| | 50 | 0.0015 | 0.838 | 80.92 | 0.4228 | 0.9966 |
| | 75 | 0.0021 | 1.034 | 68.241 | 0.5395 | 0.999734 |
| | 100 | 0.0029 | 1.302 | 53.514 | 0.8324 | 0.9980 |

5. Discussion

5.1 The constant ω^2

This parameter gives information about the dominant phenomenon such as the diffusion phenomenon which is a slower phenomenon. So, increasing the relaxation time is accompanied by a diffusion phenomenon. Whereas in the case of adsorption, the relaxation time is small (very fast phenomena) [29, 30]. The relaxation time relative to the adsorption varies according to the speed of evolution of the heat dissipated during the adsorption process (exothermic phenomenon). If the latter is small, the transfer resistance is small and depends essentially on the thermal conductivities of the adsorbate and the adsorbent [21]. Since the adsorbent is solid and the adsorbate is a gas, the smallest thermal conductivity is that of the gas adsorbate. This conductivity stops the heat dissipation to outside and the high values of thermal resistance and ω^2 are due to the fact that ω^2 and the thermal conductivity vary similarly. The variation curve of ω^2 with respect to the temperature presents two distant linear portions (Fig.4), indicating that the adsorption was not controlled only by intra-particle diffusion. The first linear portion was due to the external surface adsorption. The latter gradual linear portion refers to slow intra-particle pore diffusion [32]. These two linear portions meet at a particular temperature. It is considered as a critical temperature T_c which is an internal parameter of the couple. The origin of this critical temperature is due to variations of physico-chemical features of the adsorbent. The existence of a critical temperature for the adsorption phenomenon is observable for all the isotherms nature: static isotherm (equilibrium) or dynamical (kinetic).

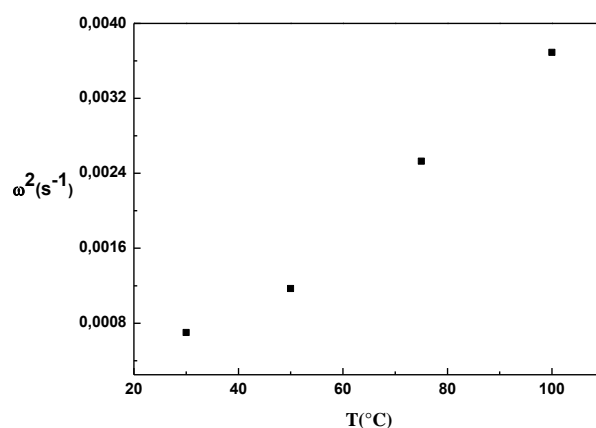
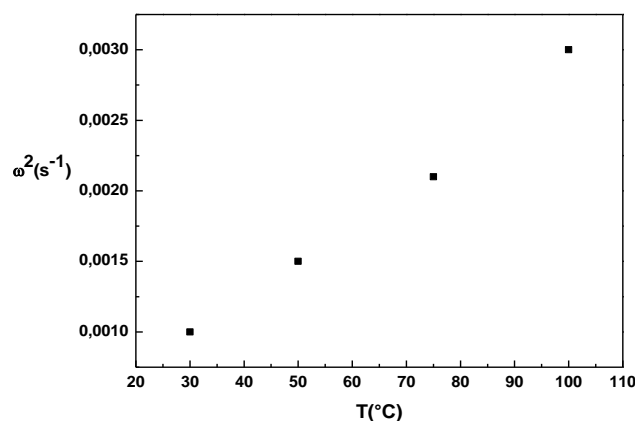


Fig 5: Evolution of ω^2 with temperature: active carbon-ethanol**Fig 6:** Evolution of ω^2 with temperature: active carbon-acetone

The term $1/\omega^2$ is the relaxation time due to the adsorbed quantity relatively to the critical temperature T_c . If the temperature T_c increases, the mass loss increases, and the specific area decreases [31]. The values of T_c and ω^2 are the coordinates of both tangent of the curve $\omega^2=f(T)$. The value of the constant f is determined from the linear equation. The differential equation which satisfies the variation curve of ω^2 with respect to the temperature [21, 28]:

$$\frac{d\omega^2}{\omega^2} = f \frac{dT}{T} \quad (8)$$

Its integration yields:

$$\omega^2 = \omega_c^2 \left(\frac{T}{T_c} \right)^f \quad (9)$$

Where ω_c^2 and f are two constants that can be determined experimentally and their values are regrouped in Table 2 for the studied couples.

Table 2: Estimation results of T_c , f and ω_c^2

| Pair | T_c (°C) | ω_c^2 (s ⁻¹) | f |
|-----------------------|------------|---------------------------------|-------|
| Ethanol-active acrbon | 50 | $1.00 \cdot 10^{-3}$ | 0.69 |
| Acetone-active carbon | 75 | $2.1 \cdot 10^{-3}$ | 0.092 |

These results enable us to conclude that the critical temperature depends much on the adsorbent but less on the adsorbate. The origin of this critical temperature is due to variations of physic-chemical characteristics of the adsorbent with respect to the adsorbate.

5.2 The constant α

This constant is measured in (m⁻¹) and then $1/\alpha$ gives the upper distance from which the molecule speed will be oriented to the center of the sphere of the microporous solid. If the distance between the adsorbent and

the adsorbate molecule is less than $1/\alpha$, the molecule movement is accelerated and the speed vector points to the adsorbent.

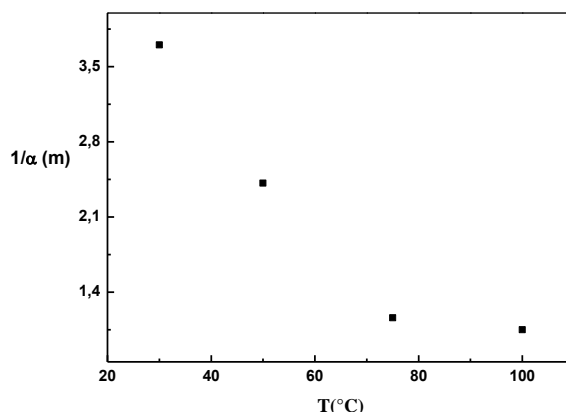


Fig 7: Evolution of $1/\alpha$ with temperature: active carbon-ethanol

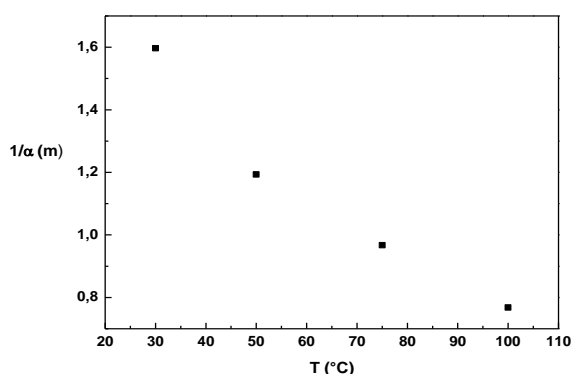


Fig 8: Evolution of $1/\alpha$ with temperature: active carbon-acetone

If the distance between the adsorbate molecule and the adsorbent is bigger than $1/\alpha$, the interaction forces adsorbate-adsorbent is equal to zero as given by the kinetic theory of gas in a homogenous and isotropic medium. The mean speed of each molecule is null. We note that $1/\alpha$ decreases once the temperature increases as shown in Fig 5. This decrease is explained by the fact that the rise of temperature prevents the adsorbate molecules to fix easily to the adsorbent surface due to thermal agitation. When the temperature increases, the interaction between the adsorbate and adsorbent surface becomes smaller as a result of the thermal agitation. Resolution of equation (3) has allowed us to establish the relationship between α and ω^2 in the following form [21]:

$$\alpha = \left(\frac{b + \omega^2}{D} \right)^{1/2} \quad (10)$$

The curve of α^2 with respect to ω^2 is a line given by Figure 6, which allows determining the values of b and D (Table 3). $\frac{1}{b}$ is a relaxation time relative to the pressure which is assumed constant (isobar adsorption) as

its variation is small for each isotherm. Since the adsorption and desorption are generally very rapid phenomena and the diffusion is a slow phenomenon. The relaxation to the diffusion, in addition to having greater amplitude, the relaxation time of the diffusion is accompanied by a strong interaction distance

adsorbate-adsorbent. In adsorption, the minimal interaction distance is important and the relaxation time is small.

Table 3: Estimation of b and D

| Pair | b | D |
|-------------------------|----------------------|----------------------|
| Ethanol - Active carbon | $-3.2 \cdot 10^{-4}$ | $3.55 \cdot 10^{-3}$ |
| Acetone- Active carbon | $-7.9 \cdot 10^{-4}$ | $3.51 \cdot 10^{-3}$ |

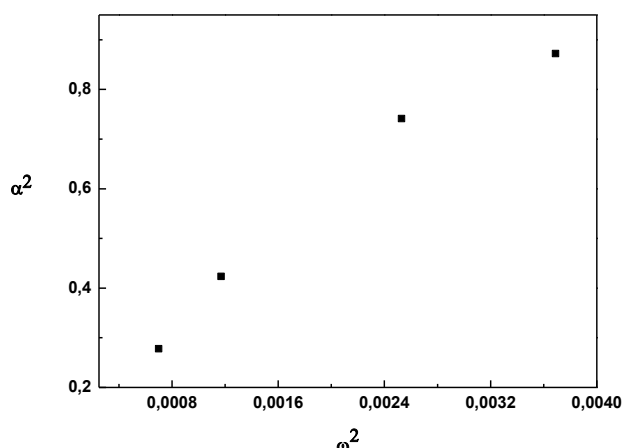


Fig 9: Evolution of α^2 with ω^2 : active carbon-ethanol

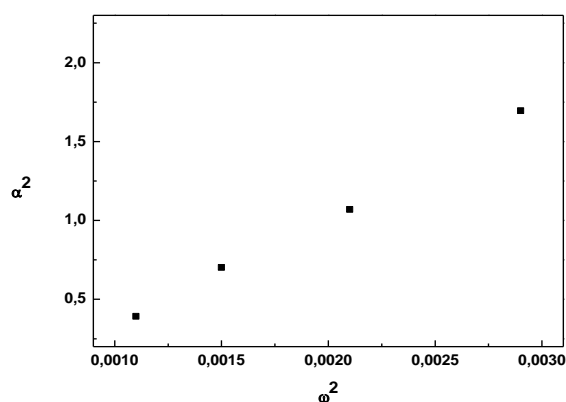


Fig 10: Evolution of α^2 with ω^2 : active carbon-acetone

Conclusion

In this paper, we confirmed the theoretical approach of simulation of the adsorbat quantity with respect to time and to the radius of the adsorbat grains. The advantage of such a study is that it takes into account the major internal parameters of the system. This is due to the use of random functions in the resolution of the differential equation imposed by fluctuation. The adsorption kinetics of ethanol in the activated carbon has been analyzed numerically by our model and compared to the experimental data. It is noted that our model has suitably described the reality. Moreover, we can affirm that the gas transportation in microporous solids is controlled by an active diffusion and molecular sieve mechanism. This model gives the proof of the existence of a characteristic temperature, the determination of adsorption minimal distance, the possibility of computing the interaction force work and the transformation of kinetic energy into heat.

REFERENCES

- [1] Z. Peng Gao, Z. Fang Yu, T. Li Yue, S. Young Quek. Journal of food Engineering 116, 1895-201(2013)
- [2] H. Radnia, A. Asghar Ghoreyshi and H.Younesi .Journal of Energy and Environment 2 (3) : 250-257 (2011)
- [3] Delage F, Pré P, Le cloirec P. Environ. Sci. Technol. Vol. 34, 4816-4821, 2000
- [4] M. Ruthven Douglas, S. Brandani and M. Eic. Methods Mol Sieves 7: 45–84 (2008)
- [5] T. Melkior, D.Mourzagh , S. Yahiaoui., D. Thoby. J.C. Alberto, C. Brouard, N. Michau. Applied Clay Science, 26, 99-107 (2004).
- [6] J.Crank. Clarendon Press, Oxford (1975) 1ère Ed.
- [7] A.P.Vavlitis, D.M. Ruthven. K.F.Loughlin. J. Colloid. Interface Sci.vol. 84, 526-531, 1981
- [8] F.M. Fowkes Syracuse Univ. Press, p.197-223 (1967).
- [9]H.W. Habgood. Chem.eng.Symp.Ser.Prog.,63, 45-51 (1967)
- [10] Douglas M R. Principles of adsorption and adsorption processes. New york, John wiley & sons Inc, 1984
- [11] Valentina V. P, Ruslan H. M, Jiri H. Adsorption science & technology. Vol. 17, 161-171, 1999.
- [12] McEwen J S, Payne S H, Kreuzer H J, Kinne M, Denecke R, Steinrück H P. Surface Science. Vol. 545: 47-69, 2003.
- [13] Javier R F., Fernando B, Olga G, Benito A, Fatima C. Water Research. Vol. 37, 4823-4834, 2003
- [14] K. Nitin, C. Alexander, M. Charles. Journal of Colloid and Interface Science. Vol. 267, 272-285, 2003
- [15] C. Xiaojun, B.R. Marc, D. Gregory. Fuel. Vol. 83, 293-303, 20047
- [16] T. Anne-claire, A. Yves, P. Le Cloirec . Environ.Sci. Technol. Vol. 33, 489-495, 1999
- [17] C. Pierre-Henri. Physica A. vol. 361, 81-123, 2006.
- [18] J. Francisco, J. Valdes-parada. O. Alberto, A. Jose. Physica A. vol. 373, 339-353, 2007.
- [19] F.M. Fowkes. Syracuse Univ. Press, p.197-223 (1967).
- [20] H.W. Habgood. Chem.eng.Symp.Ser.Prog.,63, 45-51 (1967)
- [21] F. Mhiri, A. Jemni, S. Ben Nasrallah. Journal of Porous Media. Vol. 12, 563-571, 2009.
- [22] F. Mhiri, A. Jemni. Journal of Porous Media 13(4), 295-305 (2010)
- [23] A. Nikiforov, V. Ouvarov. Fonctions Spéciales de la Physique Mathématique. Edition MIR. Mouscou (French translation), 1983
- [24] D.M .Ruthven , Post M In: van Bekkum H, Flanigan EH, Jacobs PA, Jansen JC (eds) Introduction to zeolite science and practice, 2nd edn. Elsevier, Amsterdam, p 525 (2001)
- [25] D.M. Ruthven.Wiley, New York, p 148 (1984)
- [26] Wijmans, J. G., Baker, R. W. Journal of membrane Science, 107: 1-21 (1995)
- [27] F. MHIRI, Kinetic study for the adsorption of vapour water adsorption on zeolite 13X and silica gel, IEEE 978-1-4673-1170-0/12©(2012)
- [28] F. Mhiri and A. Jemni. Environnemental Progress & sustainable Energy. 30(3):294-302 (2011)
- [29] M. Blander and J.L. Katz."Bubble nucleation in liquids". AIChE Journal, 21(5) 1975.
- [30] J.C. Fisher "The fracture of liquids" Journal of Applied Physics, 19 ,1062, 1948
- [31] P.G de Gennes and F Brochard. Phase transitions of binary mixtures in random media. J.Physiques-Lettres, 44 :L785, September 1983
- [32] M. Doke Kailas, M. Khan Ejazuddin. Arabian Journal of Chemistry, 1878-5352 (2012)