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Thermal Diffusivity and Adsorption Kinetics of Silica-Gel/Water

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Abstract. There have been performed experimental measurements of effective thermal conductivity of silica-gel for a stagnant cylindrical fixed bed under transient and steady state conditions in the presence of dry air at different pressures and for different amounts of adsorbed water. The Bauer-Schlünder and Kunii-Smith models have been used to identify the thermal solid conductivity of silica gel pellets from measurements of the conductivity in an adsorbent bed. Sorption rates of water vapor in silica gel were measured using a single-step thermal method by monitoring the sample surface temperature by infrared detection. In order to obtain the mass diffusivity it is necessary to match the numerical solution of the mathematical model to the experimental data.

Keywords: silica-gel, adsorption, conductivity, mass diffusivity

Introduction

Silica-gel is a solid adsorbent utilized as drying agent in industrial processes. Silica gel-water vapor is proposed as a working couple for solar refrigerators, heat pumps and desiccant cooling systems. The relatively regenerating temperature makes it very attractive for such applications. The analysis of the thermal behavior of devices using silica-gel shows that their performance is very sensitive on heat and mass transfer rates inside the adsorbent beads. Therefore it is necessary to measure the thermal diffusivity and sorption rates in these beads. Thermal conductivity of silica-gel from different suppliers was previously investigated by Bjürström et al. (1984) and Gurgel and Klüppel (1996). The results here presented are intended to be used in the modeling of the heat and mass transfer processes occurring in sorption systems. The silica-gel here studied is commercially known as “type R Sorbead”, produced by Kalichemie®. It is presented as spheroidal beads with an average diameter $d = 3.5$ mm, with a specific surface of 750 m^2/g, an average pore diameter of 2.0 μm, and a pore volume of 0.35 ml/g, according to what is reported by the maker (Kalichemie®. AG 1979). Bed porosity ε and density ρ_b have been found experimentally to be $\varepsilon = 0.36 \pm 0.01$ and $\rho_b = 746$ kg m^{-3} (Gurgel and Klüppel, 1996).

The present work aims at giving a contribution for determining mass diffusivity of water in silica gel and the effective thermal conductivity of the silica gel bed.

In order to measure the thermal conductivity of packed beds, a great variety of methods have been used. Those methods can be classified as steady and transient methods and are classed as very good in a review make by Tsotsas and Martin (1987). In the present work, two different techniques to measure thermal conductivity

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were considered. Measurements were performed using a technique under transient conditions for the dry bed and another technique under static conditions when there were amounts of adsorbed water in the bed. Both techniques available in the same apparatus are necessary to evaluate with good precision the thermal diffusivity and the influence of different loads of humidity. To identify the thermal solid conductivity of silica gel pellets it is necessary to use a prediction model. In this work two models are used, which were respectively developed by Sahnoune and Grenier (1988) and Bauer and Schlünder (1978). These two models are suggested (Tsotsas and Martin, 1978) by a lot of works concerning thermal conductivity of packed beds.

Mass diffusion inside the porous pellets may occur by several different mechanisms depending on the pore size, the sorbate concentration and other conditions.

The mass diffusion coefficients can be measured (Kärger and Ruthven, 1992) by either microscopic techniques (Pfeiter, 1976) and neutron scattering (Jobic et al., 1989) or macroscopic techniques (Barrer and Brook, 1953), chromatography (Schneider and Smith, 1968; Ruthven and Kumar, 1980), permeation (Hayhurst and Paravar, 1988), frequency response (Yasuda et al., 1991; Van den Begin and Rees, 1989) and zero length column (Eic and Ruthven, 1988).

In this work, the sorption rates of water vapor in silica gel, were measured by a single-step thermal method by monitoring the sample surface temperature by infrared detection. The major advantages of that technique are: no intrusive perturbations (no sensor) during the experiment, high temperature sensitivity ($\sim 10^{-3}$°C), short response constant time ($\sim 10^{-3}$ s) and the possibility to precisely focus the temperature measurement on a small region enabling the measurement of a single-pellets response. The experimental results allow obtaining the mass diffusivity by matching the numerical response of a mathematical model to experimental data. The model used in this work is a nonisothermal heat and mass transfer one developed by Sun and Meunier (1987) .

Experimental Setup for Measuring Thermal Diffusivity and Conductivity

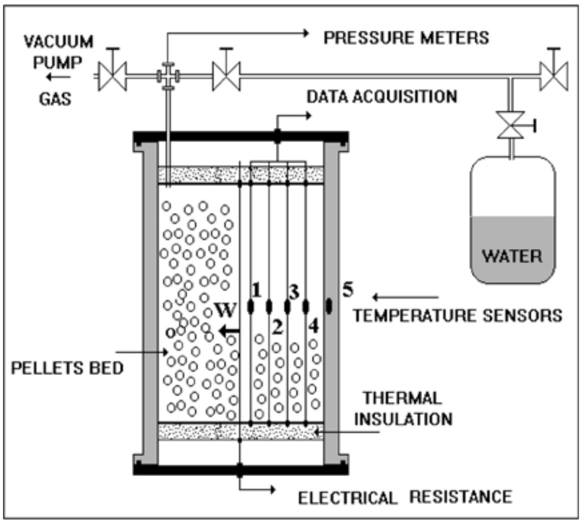

Figure 1. Experimental apparatus for thermal conductivity measurement.

The apparatus is shown in Fig. 1. It consists of a vertical cylindrical reactor designed to work under transient and steady state conditions (Gurgel and Klüppel, 1996). The sample of test material is packed as a pellet bed within a cast iron tube, 113 mm internal diameter and 400 mm height, limited at the upper and lower ends by stainless steel disks. An electrical resistance wire, 0.1 mm diameter, dissipates a heat flux in the axis of the cylinder. Five platinum 100 Ω temperature sensors are located radially in the central section of the cylinder. The sensors measure 2.0 mm diameter, and 10 mm in length and have an absolute precision of 0.3 K. The top and the bottom of the bed are well insulated in order to insure purely radial temperature gradients. The system can thus be treated as an unidimensional one (Gurgel and Klüppel, 1996) verified using a numerical solution of a two-dimensional Laplace equation in cylindrical coordinates.

Steady State Measurements to the Thermal Condutivity

Steady state conductivity measurements are performed dissipating a constant heat power Q in the axis of the sample, while the external cylinder wall is kept at constant temperature $T_5 = 27$°C. The temperatures, $T(r_i, t)$, at the radial locations r_1 to r_4 are recorded until steady state condition is attained. The conductivity of the silica bed is then calculated from the Fourier unidimensional heat conduction equation :

$$\lambda_b = \frac{Q}{2\pi L\, dT/d(\ln r)} \tag{1}$$

Where $dT/d(\ln r)$ is the decline on the temperature line, and L is the sample axial height.

Transient Measurements of the Thermal Diffusivity

For transient measurements, a thermal pulse is emitted from the heating element and the temperature at different distances from the center points are continuously recorded. The time increments between successive measurements was 5 seconds and the total transient time duration was 1200 seconds. The thermal diffusivity of the bed is calculated by the best fit of the recorded experimental data with a numerical solution of the unidimensional heat transfer equation in cylindrical coordinate. Details on this method can be found in Guilleminot and Gurgel (1990).

Description of the Apparatus and Experimental Procedure for the Mass Diffusion

The experimental apparatus developed at LIMSI (Fig. 2) by Grenier et al. (1995), consists of a variable volume chamber closed by a bellows. The adsorbent sample is placed in the chamber with a volume of 1,65 dm^{3}and its temperature is measured by IR detection. The sample is placed on a thin nickel grid with negligible heat capacity. The pressure is measured by a high precision and fast response absolute pressure gauge (Baratron®). The bellows is compressed by a sudden increase of the pressure on the external side. The compression duration is less than 20 ms. The temperature and pressure responses are fitted by a model allowing the identification of the mass transfer characteristic time (Bourdin et al., 1998).

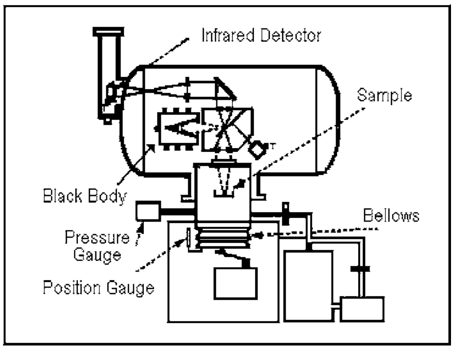

Figure 2. Experimental apparatus for mass transfer kinetics measurement.

Measurements of the Thermal Conductivity of the dry Bed in Presence of Air

The measurements under stationary heat flow yield the radial temperature gradient necessary to calculate the thermal conductivity of the packed bed, using Eq. (1). The experimental average measured value of the thermal conductivity for a bed of silica-gel under dry air at 100 kPa is $\lambda_b = 0.196 \pm 0.02$ W m^{-1} K^{-1}. The results are shown in Table 1. In order to evaluate the bulk thermal conductivity of the pellets as a function of parameters such as the thermal conductivity of the bed, the thermal conductivity of the gas, bed porosity, dimensions of the grains, two models have been used: the model of Kunii and Smith (1965) extended by Sahnoune and Grenier (1988), (**KS*** model) and the model of Bauer and Schlünder (1978), (**BS** model). These models were selected on the basis of the literature review available on the thermal conductivities of packed beds without fluid flow (Tsotsas and Marin, 1987). Both models are based on the same simplified hypothesis: the effective thermal conductivity of a packed bed, λ_b, is a function of the thermal conductivities of the fluid, λ_g, of the solid phases, λ_s, of the porosity (void fraction), ε, of the temperature, T, and of the diameter, d, of the solid particles. A unit cell is constructed (see Figs. 3 and 4) in which a portion of the heat is transferred directly through the fluid phase by conduction and radiation. In the other portion, the heat flow passes through both the fluid and the solid phases.

Both models take into account the Knudsen conductivity of the gas when the pressure is reduced, so that the mean free path of the molecules becomes non-negligible compared to the mean distance between the particles.

Table 1. Experimental results for the conductivity of an anhydrous 'sorbed R' silica-gel bed under dry air at 100 kPa.

Experiment N°	Q (W)	$dT/d(\ln r)$	λ_b W m^{-2} K^{-1}
1	1.393	6.813	0.181
2	1.793	7.336	0.215
3	2.440	11.324	0.191
4	2.850	13.029	0.193
5	4.080	18.7	0.193
6	5.567	24.32	0.202
7	6.811	30.262	0.199
Mean value			0.196

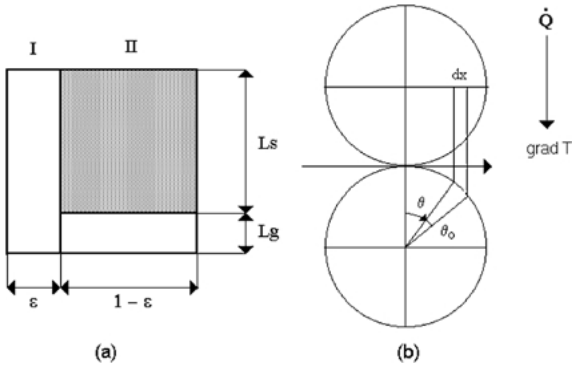

Figure 3. (a) Unit cell used by Kunii-Smith that represents the two parts of the heat transfer: direct conduction in the fluid and conduction in series solid-fluid. (b) Model for the heat transfer near a contact point.

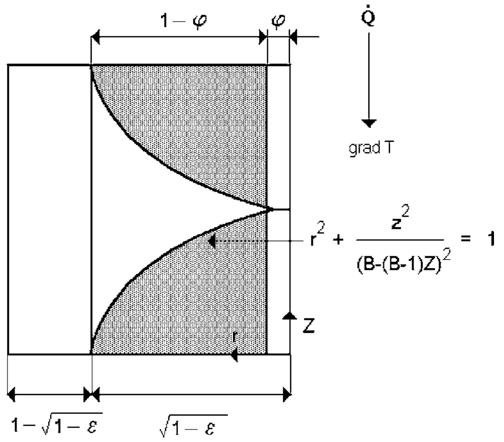

Figure 4. Unit cell used in the Bauer-Schlünder model that represents the two parts of the heat transfer: direct conduction in the fluid and conduction in series solid-fluid. The curve represents an equivalent profile of the solid particle.

KS Model (Kunii and Smith, 1965)*

For estimating the influence of a reduced pressure, the KS* model uses the following equation (Kennard, 1938):

$$\lambda_g^* = \frac{\lambda_g}{1 + \frac{2G\delta}{d_e}} \tag{2}$$

where the distance d_e is a mean intergranular distance calculated by:

$$d_e = d\left(\frac{\varepsilon}{(1-\varepsilon)}\right)^{1/3} \tag{3}$$

and

$$G = \frac{(2-\gamma)(9K-5)}{2\gamma\ (K+1)} \tag{4}$$

where γ is the accommodation coefficient, K is the ratio of the heat capacities of the gas, C_p/C_v, and δ is the mean free path of the gas molecules.

The radiative heat transfer fraction in packed beds is influenced by the temperature and geometry of the packing. For small temperatures gradients the radiative heat transfer can be described by a radiation heat transfer coefficient:

$$\lambda_{ra} = \frac{4\sigma d T^3}{\frac{2}{\varepsilon_p} - 1} \tag{5}$$

where: σ is the Stefan-Boltzmann constant and ε_p is the emissivity of the solid particles surface. For grains that are rough, as found in the practice, the value $\varepsilon_p = 0.9$ is in good agreement with the experimental findings (Muchowski, 1977).

The predictions formula for the (KS*) model becomes:

$$\lambda_b = \lambda_r + \varepsilon\lambda_g^* + (1-\varepsilon)\beta\lambda_e^* \tag{6}$$

where λ_r is a residual conductivity of small magnitude (radiation and conduction through solid contacts). It can only be obtained by experiment under vacuum. The effective thermal conductivity through the fluid film near one contact point, in series with the solid phase, is calculated by the following equation:

$$\lambda_e^* = \frac{\frac{A_1}{A^2}\ \ln\ \frac{A_1 + A\cos\theta_0}{A_1 + A} + \frac{1-\cos\theta_0}{\mathrm{A}}}{0.5\sin^2\theta_0} \tag{7}$$

with:

$$A = \frac{1}{\lambda_s} + \frac{1}{\lambda_g^*} \tag{8}$$

$$A_1 = \frac{1}{\lambda_g^*} \tag{9}$$

and

$$\theta_0 = \sin^{-1}\left(N^{-1/2}\right) \tag{10}$$

with

$$N = 6.92 - 27.45 \times (\varepsilon - 0.26) \tag{11}$$

Bauer- Schlünder Model

The prediction formula for the Bauer- Schlünder model are:

$$\frac{\lambda_b}{\lambda_g} = \left(1-\sqrt{1-\varepsilon}\right)\left[\frac{\varepsilon}{(\varepsilon-1)+\frac{\lambda_g}{\lambda_g^*}} + \varepsilon\frac{\lambda_{Ra}}{\lambda_g}\right] + \sqrt{1-\varepsilon}\left[\varphi\frac{\lambda_s}{\lambda_g} + (1-\varphi)\frac{\lambda_{so}^*}{\lambda_g}\right] \qquad (12)$$

with

$$\frac{\lambda_{so}^*}{\lambda_g} = \frac{2}{M}\left[\frac{B\left(\frac{\lambda_s}{\lambda_g}+\frac{\lambda_{ra}}{\lambda_g}-1\right)\frac{\lambda_g}{\lambda_g^*}\Big/\frac{\lambda_s}{\lambda_g}}{M^2} \times \ln\frac{\left(\frac{\lambda_s}{\lambda_g}+\frac{\lambda_{ra}}{\lambda_g}\right)\frac{\lambda_g}{\lambda_g^*}}{B\left[1+\left(\frac{\lambda_g}{\lambda_g^*}-1\right)\left(\frac{\lambda_s}{\lambda_g}+\frac{\lambda_{ra}}{\lambda_g}\right)\right]} \times \frac{B-1}{M}\frac{\lambda_g}{\lambda_g^*} + \frac{\lambda_g}{\lambda_g^*} + \frac{B+1}{2B} \times \left(\frac{\lambda_{ra}}{\lambda_g}\frac{\lambda_g}{\lambda_g^*} - B\left[1+\left(\frac{\lambda_g}{\lambda_g^*}-1\right)\frac{\lambda_{ra}}{\lambda_g}\right]\right)\right. \qquad (13)$$

with

$$M = \left[1+\left(\frac{\lambda_{ra}}{\lambda_g} - B\Big/\frac{\lambda_g}{\lambda_g^*}\right)\Big/\frac{\lambda_s}{\lambda_g}\right]\frac{\lambda_s}{\lambda_g^*} - B\left(\frac{\lambda_g}{\lambda_g^*}-1\right)\left(1+\frac{\lambda_{ra}}{\lambda_g}\Big/\frac{\lambda_s}{\lambda_g}\right) \qquad (14)$$

B is a deformation factor that changes the geometry of the unit cell (Fig. 4).

$$B = C\left(\frac{1-\varepsilon}{\varepsilon}\right)^{10/9} \qquad (15)$$

where C is a coefficient close to unity ($C = 1.25$) for spherical particles with monodispersed particle-size distribution).

The fraction of heat transfer along the solid path between particles is given by the term φ:

$$\varphi = \frac{23\rho_k^2}{1+22\rho_k^{4/3}} \qquad (16)$$

where ρ_κ^2 is the ratio between the contact area of the particle and the projected particle area along the heat flux. It can be found experimentally (Tsotsas and Marin, 1987).

The identified values for the bulk thermal conductivity of silica-gel are $\lambda_s = 0.57$ W m^{-1} K^{-1}with KS* model and $\lambda_s = 0.72$ W m^{-1} K^{-1} with BS model with a difference better than 20%. BS model offers more flexibility than KS* model because the former takes into account shape effects, nonmonodispersed packings, surface oxidation of metallic packings, radiation and low-pressure effects. Thus we estimate the best bulk thermal conductivity as: $\lambda_s = 0.65 \pm 0.15$ W m^{-1} K^{-1}.

For practical applications these results can be considered with an absolute accuracy of ±20% based in experimental works related by Sahnoune and Grenier (1988) and Gurgel and Klüppel (1996).

Measurements of the Conductivity of the Dry Bed at Different Pressures

The influence of the interstitial gas molecular effects on the bed conductivity can be verified by measuring the thermal conductivity λ_b of the bed at different pressures of a given gas. The experimental values of λ_b for dry silica-gel are plotted in Fig. 5 as a function of the total dry air pressure, from 5 Pa to 100 kPa. The curves superimposed to the experimental points are calculated with BS and KS* models, with a porosity $\varepsilon = 0.36$ and the previously identified bulk conductivity. It can be seen that the calculated curves are in good agreement with the experimental data. The two models are very sensitive to the value of the accommodation coefficient (γ) at low pressures where the Knudsen effect is present. Here was used $\gamma = 0.9$ (Bauer and Schlünder, 1978) as a function of molecular weight.

Thermal Diffusivity of the Dry Bed Under Air at Atmospheric Pressure

The thermal diffusivity α_b of the dry bed has been identified from the data given by the transient method. A thermal pulse is emitted from the heating element and the temperature history $T(r_i, t)$ at points r_1 to r_4 is continuously recorded. The thermal diffusivity of the bed is then calculated by best fit of the recorded data to a numerical solution of the heat transfer equation in cylindrical coordinates. The identified value is $\alpha_b = 2.7 \times 10^{-7}$ m^2 s^{-1}. That result and the thermal conductivity of the bed measured by the steady state method give the specific heat capacity of the bed: $C_{p_b} = 980$ J kg^{-1} K^{-1}.

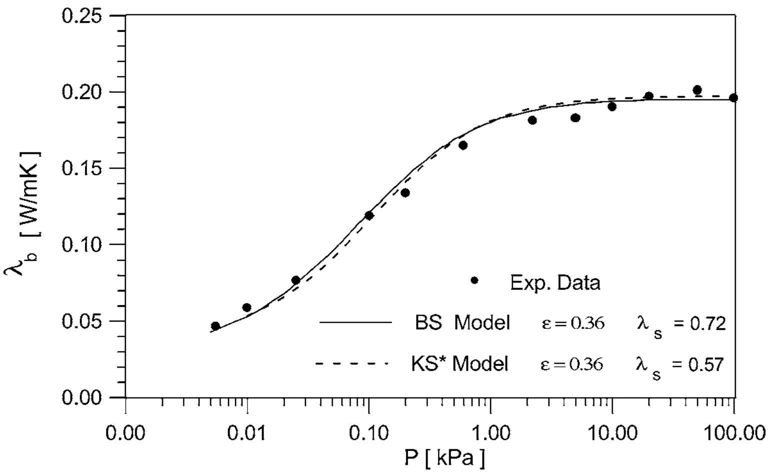

Figure 5. Thermal conductivity of a dry silica-gel bed as a function of dry air pressure.

Effect of the Water Content

The behavior of the bed conductivity in relation to the water content of the silica gel is also investigated. Steady-state measurements of λ_b are made under humid air at 100 kPa total pressure and different partial pressures of water vapor, each corresponding to a different mean water content χ_m of the silica-gel bed. The vapor pressures inside the experimental setup are theoretically calculated using Dubinin equation, with the experimental coefficients for the couple silica/water found by Khelifa (1984). It is used a water content corresponding to the arithmetic mean value of the equilibrium content of the silica at the extreme temperature T1 and T_4 in the bed. The actual pressure was measured during experiments and a disagreement smaller that 8% was found between calculated and measured values for water loads in the range $0.10 < x < 0.30$. Figure 6 shows the variation of the identified solid conductivity (for the two models) of the silica-gel grain λ_s as a function of χ_m (both models give practically identical variations, although the KS* model has shown a tendency to understimate values for solid conductivity). It can be seen that the humid pellet conductivity λ_s. increases linearly with the water content χ_m. An average expression (derived of the two model) for estimating this increase effect is obtained as: $\lambda_s = 1.4\chi_m + 0.55$ [W m^{-1} K^{-1}]

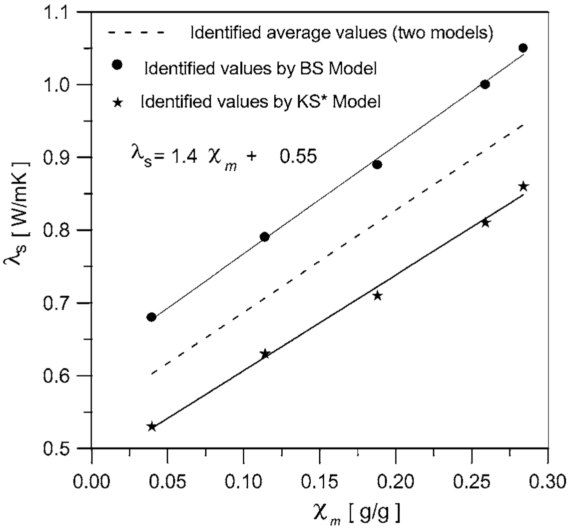

Figure 6. Solid conductivity of the silica-gel grain λ_s as a function of the mean water concentration χ_m in the silica bed.

Model for Mass Diffusivity

The model used for analyzing experimental results of mass transfer kinetics is derived from a bidispersed model developed for kinetic study of biporous zeolite pellet. Details on this model and values of parameters are given in Sun and Meunier (1987a, 1987b) and Grenier et al. (1995). In this model it is assumed that particles are spherical and have a uniform size. The driving force is the chemical potential gradient. The porous structure of the silica-gel particles is not well known, and thus a monodispersed model has been used. The main equations governing the process areas follows:

- Mass balance:

$$\frac{\partial}{\partial t}\left(\frac{PV}{RT} + V_s q\right) = 0 \tag{17}$$

- Mass diffusion

$$\frac{\partial q}{\partial t} = \frac{D_e}{r_p^2}\frac{\partial}{\partial r_p}\left(r_p^2\frac{\partial q}{\partial r_p}\right) \tag{18}$$

with boundary conditions:

$$\left.\frac{\partial q}{\partial r_c}\right|_{r_c} = 0; \qquad q|_{r_c=R_c} = q^* \tag{19–20}$$

where P and T are the pressure and temperature of the gas, V_s is the sample volume R_c is the pellet radius, and q is the adsorbate concentration. R is the ideal gas constant and D_e is the effective diffusivity. The concentration q^* at equilibrium is given by the state equation. Because the changes of pressure and temperature after the step are small, the state equation can be linearized as:

$$q^*(P, T) = q^*(P_0, T_0) + K_P(P - P_0) - K_T(T - T_0) \tag{21}$$

where index 0 refers to initial conditions.

- Heat diffusion:

$$C_s\frac{\partial T_s}{\partial t} - |\Delta H|\frac{\partial q}{\partial t} = \frac{\lambda}{r_c^2}\frac{\partial}{\partial r}\left(r_c^2\frac{\partial T}{\partial r_p}\right) \tag{22}$$

with corresponding boundary conditions:

$$\left.\frac{\partial T_s}{\partial r_p}\right|_{r_c=0} = 0; \qquad -\lambda\left.\frac{\partial T_s}{\partial r_p}\right|_{r_c=Rc} = h\left(T_s|_{r_c=R_c} - T_0\right) \tag{23–24}$$

where C_s is the overall volumic heat capacity of the sample (adsorbent + adsorbate), ΔH is the heat of sorption and h is the overall heat transfer coefficient (conductive + radiative).

Mass Transfer Results

Table 2. Parameters of the experiments on Silica gel—water and identified diffusivity. P_0, T_0 and q_0 are the pressure temperature and water concentration respectively before the volume step. P_M is the maximum pressure just after the bellows compression.

Exp.	P_0 (Pa)	T_0 (°C)	q_0 (kg/m^3)	P_M (Pa)	τ (s)	D_e (m^2/s)
N° 1	96.33	30	0.031	105.9	21	9.7×10^{-9}
N° 2	326.0	30	0.069	358.0	90	2.3×10^{-9}
N° 3	993.0	30	0.149	1092.0	110	1.9×10^{-9}

The global mass-transfer characteristic time is obtained directly from an experiment on pellets, and it is the information required for most of column dynamic work (Sun, 1988). The characteristic time of diffusion in a spherical grain is bound directly to the coefficient of microporous diffusion. In this work, the mass transfer characteristic time τ has been identified from pressure and temperature curves for 3 experiments. As indicated previously, it has been assumed that the silica-gel structure was monodispersed. Thus, to a mass transfer characteristic time corresponds an effective diffusivity D_e:

$$D_e = \frac{1}{15}\frac{R_c^2}{\tau} \tag{25}$$

Table 2 gives the main parameters of the experiments, the identified mass transfer characteristic time, τ, and the corresponding effective diffusivity D_e.

Figure 7 shows the pressure and temperature responses after the step N° 3 and the curves calculated with the diffusivity given in Table 1 and using the model developed by Sun (Grenier et al., 1995).

One can see that the experimental data are well fitted by the calculated curves showing that the mass transfer

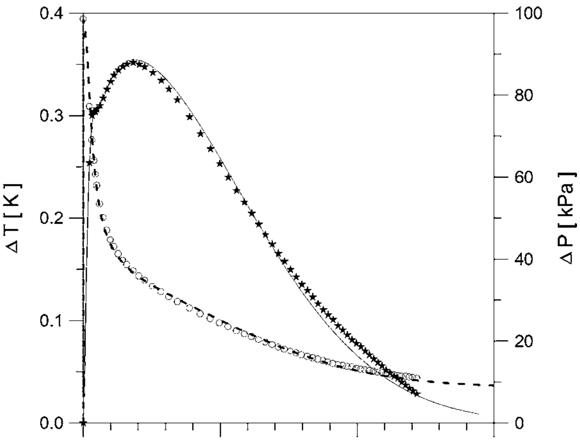

Figure 7. Temperature response of 3.5 mm diameter silica gel pellets after a pressure step of water vapor (Exp. N° 3). Initial conditions: 993 Pa and 30°C. Identified mass transfer characteristic time, τ. 110 s. Dots:experimental data; lines: calculated curves. (∗ ∗ ∗) and (——): temperature; (ooo) and (- - -): pressure.

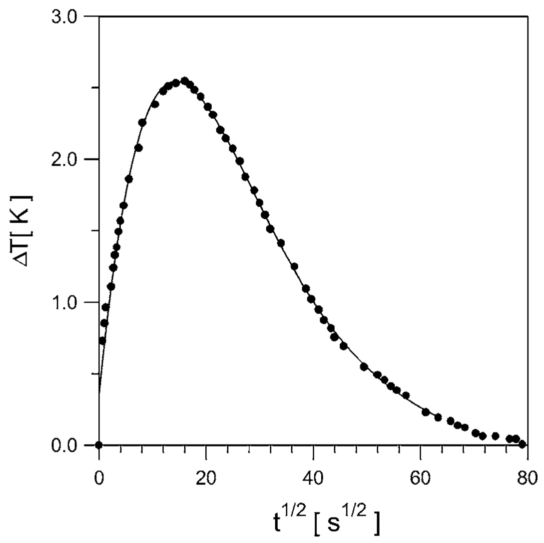

Figure 8. Temperature response of 4.0 mm diameter NaX zeolite pellets after a pressure step of water vapor (115–154 Pa). Identified mass transfer characteristic time, τ: 405 s.

can be well described by a diffusion law but it can not be decided if the dominant diffusivity occurs at microporous or at macroporous level. For a better investigation of this question, it would be necessary to know details of the pores structure.

The mass transfer characteristic time increases with water pressure and ranges between 20 and 100 s. In cases of cyclic processes, it should be necessary to use smaller beads to reduce the mass transfer characteristic times. It is interesting to compare the kinetics of water in silicagel with the kinetics of water in NaX zeolite. Figure 8 shows the temperature response obtained after a 115–154 Pa pressure step of water in NaX zeolite pellets ($d = 4$ mm) measured by (Grenier et al., 1995). This curve is well fitted introducing in the model a mass transfer characteristic time $\tau_m = 405$ s. This characteristic time is much larger than that obtained with silica gel (Table 1) and it is thus very attractive to utilize the silica gel as adsorbent for cooling desiccant systems if the regenerating process can be carried out at temperatures around 100°C.

Conclusion

Measurements of the thermal conductivity of packed silica-gel beds show that the bed conductivity increases with the gas pressure at low pressure. Using two models giving the thermal conductivity of a bed from the thermal conductivities of the particles and of the gas (Bauer and Schlunder, 1978; Kunii and Smith, 1965), it has been possible to determine the bulk conductivity of the silica-gel beads. It has been found an almost linear increase of the bulk conductivity of the beads with water concentration in the sorbent.

Using a volume step method, mass transfer characteristic times of adsorbed water in the silica-gel beads have been determined and found to be comprised between 20 s and 110 s, depending on the pressure. A mass diffusion law accounts well for the mass transfer.

Nomenclature

B	Deformation factor changing the geometry of the unit cell	–
C	Geometrical coefficient	–
C_p	Specific heat capacity	J kg^{-1} K^{-1}.
C_s	Overall volumic heat capacity	J K^{-1} m^{-3}
d	Beads average diameter	mm
d_e	Mean intergranular distance	mm
D_e	Effective diffusivity	m^2 s^{-1}
h	Overall heat transfer coefficient	W m^{-2} K^{-1}
K	Ratio of the heat capacities of the gas	(C_p/C_v)
N	Number of contacts points	–
P	Gas pressure	kPa
Q	Heat power	W
q	Adsorbate concentration	kg m^{-3}
r	Current radius	m
R	Ideal gas constant	J Kg^{-1} K^{-1}
R_c	Pellet radius	m
T	Gas temperature	K
V_s	Sample volume	m^3
α	Thermal diffusivity	m^2 s^{-1}
χ_m	Relative mean water content	–
δ	Mean free path of the gas molecules	μm
ΔH	Mass sorption enthalpy	J Kg^{-1}
ε	Bed porosity	–
ε_p	Emissivity of the surface solid particles	–
γ	Accommodation coefficient	–
φ	Describes the additional heat transfer through the solid path between particles	–
λ	Thermal conductivity	W m^{-2} K^{-1}
λ_g	Thermal conductivity of the gas	W m^{-2} K^{-1}
λ_g^*	Thermal conductivity of the gas at reduced pressure	W m^{-2} K^{-1}

λ_r	Residual thermal conductivity	$W\ m^{-2}\ K^{-1}$
λ_{ra}	Radiative equivalent thermal conductivity	$W\ m^{-2}\ K^{-1}$
λ_s	Thermal conductivity of solid particle	$W\ m^{-1}\ K^{-1}$
ρ	Density	$kg\ m^{-3}$
ρ_κ^2	Contact area	–
σ	Stefan-Boltzmann constant	$W\ m^{-2}\ K^{-4}$
τ	Characteristic time	s

Subscript

$_0$	For the properties before the volume step
b	For the bed properties

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