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Estimation of moisture diffusivity in gelatin–starch gels using time-dependent concentration–distance curves at constant temperature

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Abstract

Mass transfer in food systems is generally described using Fick's laws with an effective mass transfer coefficient. There is no standardized method for estimating diffusivity. The published values present a huge variability which is due to the diversity of experimental methods, and variability of products (structure, composition). In this paper, different methods for measuring moisture diffusivity in solid products are briefly presented and discussed. The evolution of experimental moisture profiles in different solid matrices (gelatin and mixed starch and gelatin gels), using a diffusion cell at 10 or 20 °C, was analyzed. The obtained time-dependent water concentration profiles were used for estimating the diffusivities of water for each matrix. Moisture diffusivity varied from 7.5×10^{-11} to 3×10^{-11} m^2/s in the range of 9.1 kg water/kg DM to 4.3 kg water/kg DM in gelatin and starch gelatin gels at 20 °C and from 5×10^{-11} to 1×10^{-11} m^2/s in the range of 5.2 kg water/kg DM to 2.5 kg water/kg DM in gelatin gels at 10 °C. Significant effect of temperature was observed on moisture diffusivity but, for the studied matrices, the composition was found to have no significant effect on moisture transfer rates.

Keywords: Drying; Moisture diffusion; Starch–gelatin gels; Concentration–distance curves

1. Introduction

1.1. General

Mass transfer is extremely important in food processing. Information on water migration is needed for controlling the processes and the final quality of products. In heat processing (drying, freezing, cooking), packaging, osmotic dehydration, brining and dry-salting, moisture transfer must be controlled to avoid quality deterioration and to contribute to the development of new properties of the product (colour, flavour, texture).

The use of an average moisture diffusivity, found in literature for the same or a comparable material, is usually sufficient for routine engineering calculation. But, for some processes, such as osmotic dehydration, brining or dry-salting, knowledge of the moisture distribution within the product versus time allows the control of the process and of the food properties.

The knowledge of the local moisture and solute contents, as a function of the spatial position within the product, measured during a brining or dry-salting process, can be used for the determination of moisture and solute diffusivities. These coefficients are used for predicting the time required to obtain the desired composition (salt and moisture) in the product or the product composition (salt and moisture) after a known time of treatment (Gros and Dussap, 1984; Gros and Ruegg, 1987).

The published data of moisture diffusivity in food products present a huge variability. Zogzas, Maroulis and Marinos-Kouris (1996) showed that the majority of the values vary from 10^{-12} to 10^{-8} m^2/s, with a fairly normal shape distribution around the mean value of 7.9×10^{-9} m^2/s. This variability depends on:

- Types and conditions of experimental procedures used for the determination of the moisture diffusivity: determination from the average moisture content or from the moisture profile within the product.
- Data treatment methods: resolution of Fick's equations using analytical or numerical methods,

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Nomenclature

DM	Dry matter
D	Moisture diffusivity (m^2/s)
S	Section of a slice (m^2)
S/G	Starch – gelatin ratio
m_i	Mass of a slice (kg)
t	Time (s)
ΔX_w	Initial difference in moisture content (kg water/kg DM)
X_i	Moisture content of a slice at time t (kg water/kg DM)
X_0	Initial moisture content (kg water/kg DM)
Δx_i	Thickness of a slice (m)
$\rho(X_i)$	Density of gel (kg/m^3)
ρ_w	Density of water (kg/m^3)
ρ^*	Density of anhydrous gel (kg/m^3)
ε	Retraction coefficient
x_i	Wet length (m)
ξ_i	Solid length (m)
η_i	Boltzman variable ($m.s^{-1/2}$)

Indices

1:	Referring to gel 1
2:	Referring to gel 2

taking (or not) shrinkage of the material into account, considering a variable or a constant diffusivity. Zogzas and Maroulis (1996) studied the influence of the different possibilities for the estimation of moisture diffusivity using four different models. They showed that numerical resolution of the equation of diffusion is more adapted for shrinking materials, for which the moisture diffusivity strongly varies with moisture content.

- Variability of the product: composition (water and solutes), state of ripeness of fruits and meat, heterogeneity of the structure. Ruiz Cabrera (1999) showed that the moisture diffusivity in pork muscle was independent of the fibres orientation. On the other hand, Gou, Mulet, Comaposada, Benedito, and Arnau (1996) showed that the moisture diffusivity, measured in the direction of the fibres, was double of that measured in the perpendicular direction.

Moisture diffusivity in solid foods can be determined by different methods involving defined geometries, and well-defined experimental conditions (steady state or transient conditions). The most frequently used methods for moisture diffusivity determination in solid foods are briefly presented here. More details on different experimental procedures and data treatment methods can be found in many papers (Crank, 1975; Doulia, Tzia & Gekas, 2000; Gekas, 1992; Gros & Ruegg, 1987; Zogzas & Maroulis, 1994).

1.2. Permeation method

This method consists in placing a thin sheet of solid material between two containers with media maintained at constant concentration and temperature. After a certain period of time, a steady state is attained. A constant linear gradient of concentrations is developed in the material and the surfaces of the film are in equilibrium with the diffusing sources. The method is always applied in packaging to determine gaze permeability through a thin sheet. Diffusivity (or permeability) is determined by applying the first Fick law as described by Crank (1975).

Manufacturing of an homogeneous film with a well known thickness and a perfect sealing of the film edges is necessary to ensure an homogeneous permeation in all points of the area sheet. The major difficulty of the experimental procedure is to set up and to maintain the steady state conditions.

Most authors also neglect to take into account the presence of boundary layers on both sides of the film, which change the partial pressure at the surface and distort the identified value of diffusivity.

1.3. Sorption/desorption and drying method

The permeation, sorption/desorption and drying methods are based on the measurement of the average moisture content of the sample for estimating the flux. The weight of the sample with a well defined geometry is measured at regular times in order to evaluate the moisture uptake (in sorption cases) or the moisture loss (in desorption and drying cases) until the final equilibrium is reached, i.e. when the mass of the sample remains unchanged. In sorption/desorption cases, the experimental procedure consists in suspending a plane thin sheet in an atmosphere maintained at controlled pressure and temperature.

In the case of drying, which is a particular desorption case, the moisture loss is measured under constant and controlled air conditions (temperature, velocity and humidity). The falling rate period of the experiment is used, while the drying rate is controlled by the transport of water within the material.

In the case of an infinite slab, assuming one-dimensional moisture movement without volume change, a constant diffusivity, uniform initial moisture distribution and negligible external resistances, the analytical solution of the equation of diffusion can be approximated by (Crank, 1975):

$$\ln\left(\frac{X_e - X}{X_e - X_0}\right) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D t}{L^2} \qquad (1)$$

where X (kg/kg DM) is the average moisture content at time t, X_e (kg/kg DM) is the moisture content at equilibrium, X_0 (kg/kg DM) is the initial moisture content and L is the half thickness of the sheet.

For the time $t_{\frac{1}{2}}$ corresponding to half-equilibrium relation, (1) is written:

$$D = 0.049\frac{L^2}{t_{\frac{1}{2}}} \tag{2}$$

Diffusivity can be calculated using relation (2). Relation (1) can also be used to determinte effective moisture diffusivity from the slope $(\frac{\pi^2 D}{L^2})$ of the curve of the logarithm of the reduced concentration plotted as a function of time $\ln\left(\frac{X_e - X}{X_e - X_0}\right) = f(t)$.

In drying, average or variable diffusivity versus moisture content can be determined numerically by minimizing the sum of the squares of the deviation between the experimental and the theorical drying kinetics of the material. The major difficulty of the drying procedure is to maintain a constant surface concentration during the experiment. Food products are also often shrinking materials for which the moisture diffusivity varies with the moisture content. In sorption/desorption cases, the homogeneity of the atmosphere can be maintained by stirring. The value of diffusivity is also very sensitive to the precision on the measurement of the thickness of the slab.

It is important to notice that all these methods are also based on the assumption that the external resistance to moisture transfer is negligible, which is not always proven.

1.4. Concentration—distance curve method

The concentration–distance curve method consists in measuring, at a time t, the moisture concentration profile within the sample as a function of distance during a one-dimensional unsteady state diffusive process. This method can be applied to moisture or solutes (e.g. salt, sugar) diffusion.

The concentration–distance curve can be obtained using two semi-infinite cylinders of material of the same dimensions (radius and length). A cylinder of material, containing an initially uniform concentration of the diffusing substance (C_0), is placed in contact with a cylinder free of solute or maintained at lower concentration (C_1). The diffusion occurs essentially along the axis of the joined cylinders. After a period of time t, the solute concentration profile along this axis can be determined by slicing and weighing the samples. The experimental difficulties are mainly due to slicing. Magnetic resonance imaging (MRI) can also allow a non-destructive measurement of the moisture profiles (Ruiz Cabrera, 1999).

There is no standard method for evaluating diffusivity. The choice of the experimental procedure depends on the particular needs of the experiment. The time-dependent concentration–distance curve is a simple and an inexpensive method, which can provide more information about water or other solute movement within the product.

Diffusivity can be evaluated from experimental data using numerical or analytical solutions of Fick's laws of diffusion. The numerical method (finite elements or finite differences) is of great interest in multidimensional diffusion phenomena. Numerical methods are not restricted to specific geometries or boundary conditions, such as the analytical ones.

The aim of this paper is to obtain, using a simple and robust method, quantitative information about migration of water in different matrices of starch and gelatin gels, for which affinity to water may be different. In this study, the concentration–distance curve method was retained to evaluate moisture diffusivity. The data treatment method, used to determine moisture diffusivity from experimental moisture profiles, is explained in the Materials and methods section.

2. Materials and methods

2.1. Gel preparation

Gels were prepared in a viscoamylograph device (Brabender, Duisburg, type VA1, Germany) as follows:

- dispersion of corn starch and/or gelatin (60 or 175 Bloom, type A, pork skin) powders in water at 25 °C;
- heating until 80 °C (1.5 °C/ min);
- stirring 30 min at 80 °C (75 rot/min);

Plexiglas's cylinders (55 mm × 25 mm) were filled with the solutions and closed with Teflon stoppers before storage for 24 h at 5 °C.

A preliminary study of the evolution of Young's modulus, calculated from penetrometry experiments, showed that gels were stabilized after 24 h of storage at 5 °C. Moreover, the gels remained stable during storage for at least two weeks at 20 °C, whatever the starch–gelatin ratio (ratio S/G = 1, 2 and 4). These gels were retained for studying the migration of moisture using a diffusion cell.

Different compositions of gels were chosen in order to study the influence of water adsorption properties and the mechanical properties of the matrices.

2.2. Diffusion cell

Two cylinders of gels of the same material, but of different initial moisture concentrations, were placed end-to-end in a glass tube closed with a plastic stopper and stored at a constant temperature (10 or 20 °C)

[Fig. 1 (a)]. A perfect contact between the two gels was required to obtain repeatable results. Before putting the two gels into contact, smooth and flat surfaces orthogonal to the axis of the cylinders were made using a razor blade.

After different durations (from 1 to 29 days), the two cylinders of gels were removed from the glass tube and each gel was cut into about 25 slices (20 slices of 1 mm, close to the contact interface, and then 5 slices of 5 mm thickness), using a microtome and a razor blade [Fig. 1 (b)].

Moisture content was analyzed on each slice after drying in an oven (24 h at 105 °C). The moisture content (kg/kg DM) in each slice was plotted against the distance, x, of the centre of the slice from the surface.

2.3. Experimental conditions

The experimental conditions used for moisture measurements are summarized in Table 1. Precision on measurements was about ±0.07 kg of water/100 kg of wet gel. Each profile was repeated two or three times. Only one repetition for each time is reported in the next figures.

2.4. Data treatment method

Concentration–distance curve method was used to determine moisture diffusivity from the experimental moisture profiles.

For a variable diffusivity, $D(X_i)$ can be evaluated at a specific concentration X_i obtained at time t using the following equation (Crank, 1975):

$$D(X_i) = -\frac{1}{2t}\frac{\mathrm{d}x}{\mathrm{dX_i}}|_{\mathrm{X=X_i}}\int_{\mathrm{X_0}}^{\mathrm{X_i}} x\mathrm{dX_i} \tag{3}$$

If the moisture concentration is initially constant and if concentration remains constant in the ends of the cylinders, the Boltzman transformation can be applied and Eq. (3) becomes:

$$D(X_i) = -2.\frac{\partial\eta}{\partial X_i}|_{X=X_i}\int_{X_0}^{X_i} \eta\partial X_i \tag{4}$$

with $\eta = \frac{x}{2\sqrt{t}}$, which is the Boltzman variable (Crank, 1975)

Shrinkage can also be taken into account by using Lagrangian coordinates related to the dry matter. For

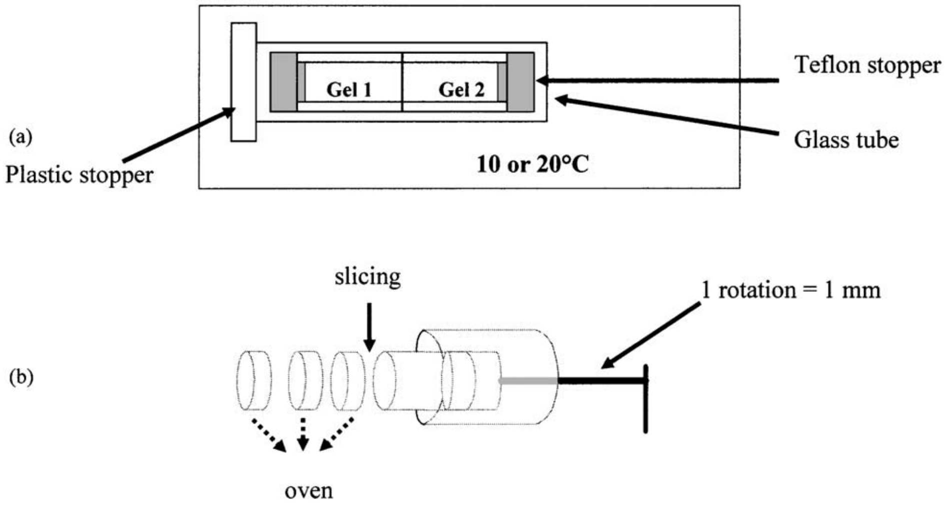

Fig. 1. The diffusion cell method: diffusion cell (a) and slicing device (b).

Table 1
Experimental conditions of moisture profiles measurements

Matrices	ΔX_w (g/100g of wet gel)	Temperature (°C)	Time of analysis	Number of experiments
Gelatin 60 Bloom	5	20	0, 3, 7 days	2
	10	10		
		20	0, 3, 14 days	3
Gelatin 60 Bloom	3	10	10, 17, 29 days	2
Gelatin 175 Bloom	5	20	0, 3, 7 days	2
Starch-Gelatin 60 Bloom (S/G = 4)	4			
		20	0, 1 and 3 days	2
Starch-Gelatin 60 Bloom (S/G = 0.1)	4			
		20	0, 3, 7 days	2

moisture diffusion, it can be expressed by using $\Delta\xi_i = \frac{\Delta x_i}{1+\varepsilon.X_i}$ (Ruiz Cabrera, 1999), where ε is the coefficient of retraction of the material. This coefficient assumes that the change in volume corresponds to the amount of the moisture lost by the material (Kechaou, 1989). In that case, Eq. (4) becomes:

$$D(X_i) = -2.\frac{\partial\eta}{\partial X}|_{X=Xi}\int_{X_0}^{X_i}\eta_i\partial X_i \times (1+\varepsilon X_i)^2 \qquad (5)$$

with $\eta_i = \frac{\xi_i}{2\sqrt{t}}$.

D is evaluated as a function of concentration by repetitive use of either Eqs. (3), (4) or (5). The variations of $D_i = f(X_i)$ are therefore obtained without any a priori form of the f function. Eq. (5) was retained in this study for evaluating moisture diffusivity.

3. Results and discussion

3.1. Moisture profiles

Repeatable profiles were obtained for different experimental conditions. Fig. 2 shows five repetitions of the moisture profile in a gelatin gel, measured after 3 days at 20 °C. Fig. 3 shows the influence of temperature. Moisture migration in gelatin is faster at 20 °C than at 10 °C. The increase of the initial difference in moisture content from 3 to 5% and 10% in gels of gelatin also accelerated the moisture transfer. Results obtained for different matrix compositions showed that the ratio of starch and gelatin (S/G = 1 or 4) and the rigidity of the gel (60 or 175 Bloom) had no significant effect on the rates of moisture transfer at 20 °C.

Fig. 4 shows the moisture profiles gelatin gel after 3, 7 and 14 days at 20 °C plotted versus wet length. The same profiles plotted versus Boltzman variable ($\eta_i = \frac{\xi_i}{2\sqrt{t}}$) (Fig. 5) show that the time-dependent curves were all gathered in one major curve.

3.2. Estimation of moisture diffusivities

The moisture diffusivities were calculated from time-dependent water concentration profiles as described by Crank (1975) and adapted by Ruiz Cabrera (1999) for shrinking materials [Eq. (5)]. This method provides the variation:$D_i = f(X_i)$, without any a priori form of f function. At first, the exact thickness of each slice was calculated from its mass using the relation: $\Delta xi = \frac{m_i}{S\rho(X_i)}$, where $\rho(X_i) = 1430.\frac{1+X_i}{1+1.43.X_i}$ (Ruiz Cabrera, 1999).

Profiles were then transformed in solid length [Lagrangian coordinates: (ξ, t)] in order to take into account the shrinkage of the gel by using: $\Delta\xi_i = \frac{\Delta x_i}{1+\varepsilon.X_i}$, where $\varepsilon = \frac{\rho^*}{\rho_w}$

ρ_w	Density of water (kg / m^3)
ρ^*	Density of anhydrous gel (kg / m^3)
ε	Retraction coefficient

The profiles were then plotted versus Boltzman variable ($\eta_i = \frac{\xi_i}{2\sqrt{t}}$) and the moisture diffusivity was determined on the basis of fitted profiles plotted versus Boltzman variable. The moisture profiles in gels 1 (desorption) and 2 (sorption) were fitted using, respectively, the equations:

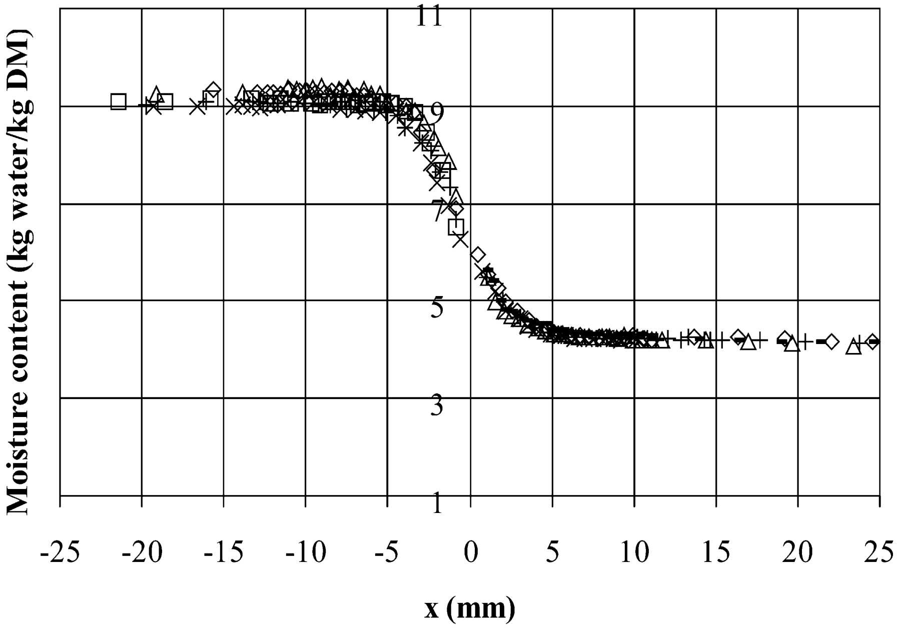

Fig. 2. Repeatability of the method for moisture content profile measurement (3 days at 20 °C) in gelatin gels (five repetitions).

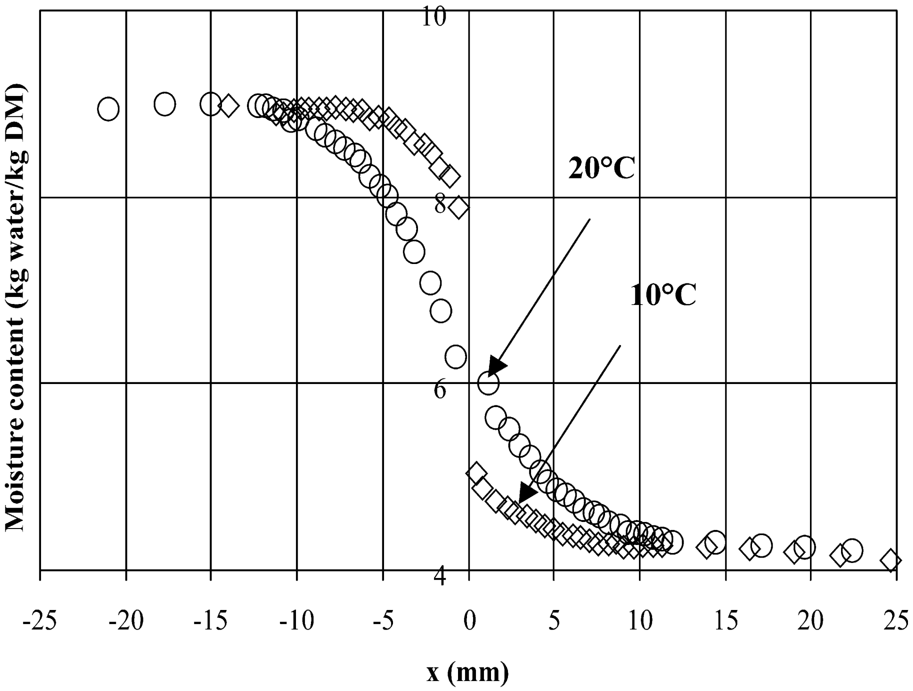

Fig. 3. Effect of temperature (14 days at 10 and 20 °C) on moisture content profile in gelatin gels, initial difference in moisture content = 10%.

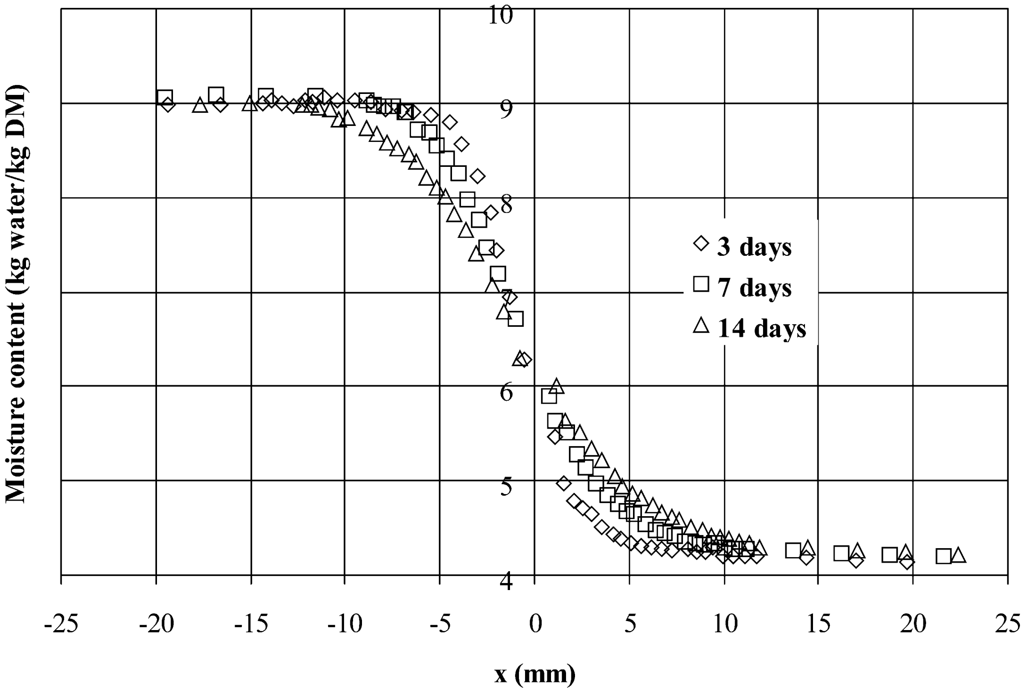

Fig. 4. Moisture content profile plotted in wet length in gelatin gels after 3, 7 and 14 days at 20 °C, initial difference in moisture content = 10%.

$X_{i1} = X_{01}(1 - a_1\exp(b_1\eta_{i1}))$ and
$X_{i2} = X_{02}(1 + a_2\exp(b_2\eta_{i2}))$

And moisture diffusivity was calculated using Eq. (5):

$$D(X_i) = -2.\int_{X_0}^{X_i} \eta_i \partial X_i \frac{\partial \eta}{\partial X}|_{X=X_i} \times (1 + \varepsilon X_i)^2$$

The term $(1 + \varepsilon X_i)^2$ allows expressing D_i in Eulerien coordinates (x, t).

The slopes $\frac{\partial\eta}{\partial X}|_{X=X_i}$ and the areas $\int_{X_0}^{X_i}\eta_i\partial X_i$ (Fig. 6), required for calculating D_i from Eq. (5), were calculated from the functions: $\eta_{i1} = A_1 + B_1\ln\left(1 - \frac{X_{i1}}{X_{01}}\right)$ for gel 1 and $\eta_{i2} = A_2 + B_2\ln\left(\frac{X_{i2}}{X_{02}} - 1\right)$ for gel 2, where $B_1 = \frac{1}{b_1}$; $A_1 = \frac{1}{b_1}\ln\frac{1}{a_1}$ and $B_2 = \frac{1}{b_2}$; $A_2 = \frac{1}{b_2}\ln\frac{1}{a_2}$.

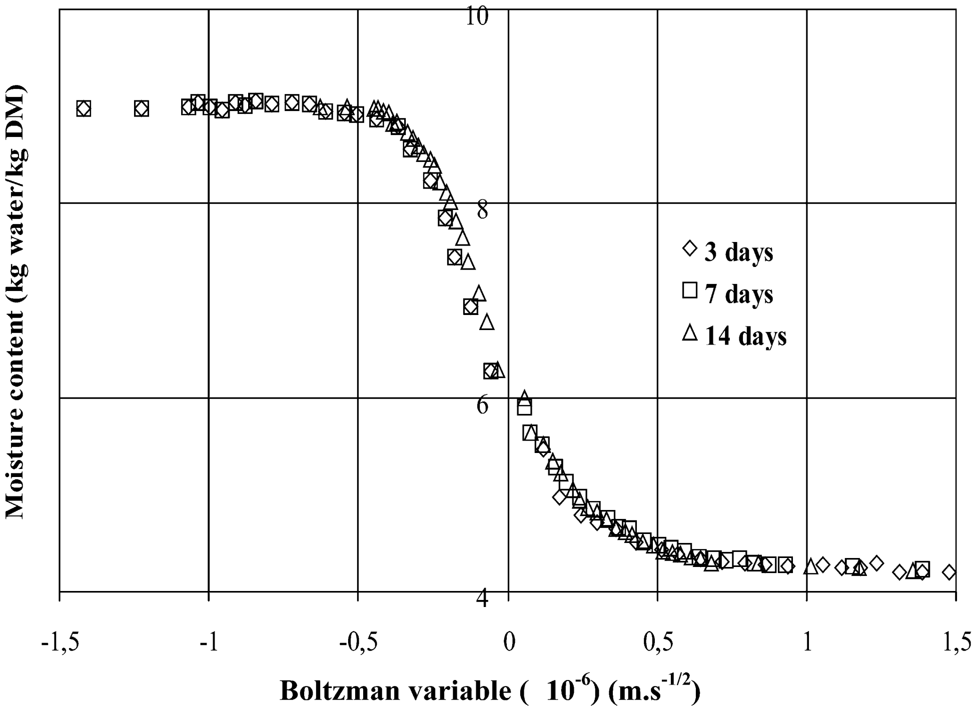

Fig. 5. Moisture content profile plotted versus Boltzman variable in gelatin gels after 3, 7 and 14 days at 20 °C, for an initial difference in moisture content = 10%.

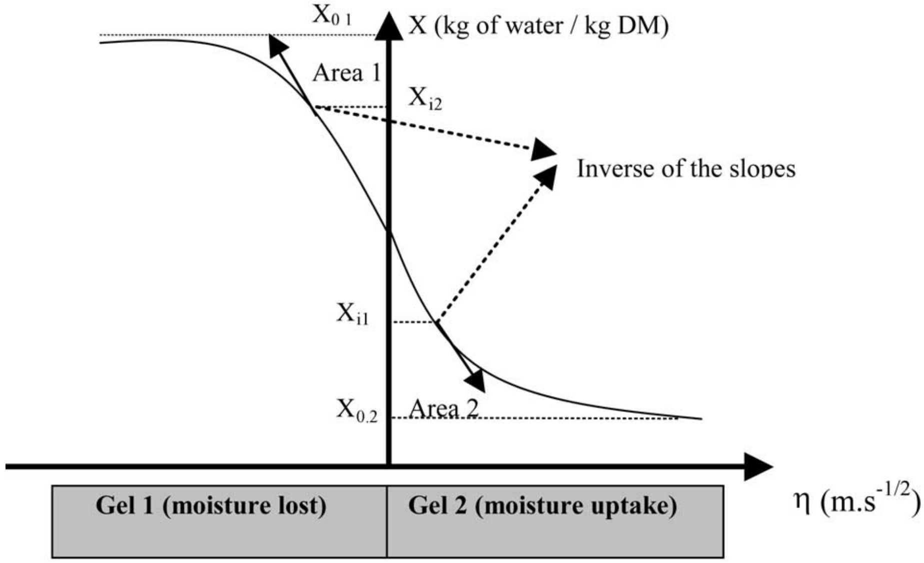

Fig. 6. Concentration–distance curve method: evaluation of moisture diffusivity in the two cylinders of gels.

A_1, B_1, A_2, B_2 were identified by minimizing the sum of the squares of the deviation between the experimental and the fitted moisture profiles.

Relations (6) and (7) were obtained by applying relation (5), respectively, to gels 1 and 2.

$$D_1 = \left[-2B_1A_1 - 2B_1^2\left(\ln\left(1 - \frac{X_{i1}}{X_{01}}\right) - 1\right)\right] \times (1 + \varepsilon X_{i1})^2$$
for gel 1

(6)

$$D_2 = \left[-2B_2A_2 - 2B_2^2\left(\ln\left(\frac{X_{i2}}{X_{02}} - 1\right) - 1\right)\right] \times (1 + \varepsilon X_{i2})^2$$
for gel 2

(7)

by calculating the slopes and the areas as follows:

Slopes:

$$\frac{\partial\eta}{\partial X}|_{X=X_{i1}} = -\frac{B_1}{X_{01} - X_{i1}} \text{for gel 1}$$

$$\frac{\partial \eta}{\partial X}|_{X=X_{i2}}=\frac{B_2}{X_{i2}-X_{02}}\text{forgel 2}$$

Areas:

$$\int_{X_{01}}^{X_{i1}} \eta_{i1}\,\partial X_{i1}=\left[A_1+B_1\left(\ln\left(1-\frac{X_{i1}}{X_{01}}\right)-1\right)\right]\times(X_{i1}-X_{01})$$

for gel 1;

$$\int_{X_{02}}^{X_{i2}} \eta_{i2}\partial X_{i2}=\left[A_2+B_2\left(\ln\left(\frac{X_{i2}}{X_{02}}-1\right)-1\right)\right]\times(X_{i2}-X_{02})$$

for gel 2;

The moisture diffusivities in gels were estimated using relations (6) and (7) and taking the shrinkage of gel into account as described in the data treatment section. Moisture diffusivities varying from 7.5×10^{-11} to 3×10^{-11} m^2/s were obtained for gelatin and starch–gelatin gels for moisture contents varying between 9.1 and 2.5 kg water/kg DM. Figs. 7 and 8 show the variations of the moisture diffusivity at 10 and 20 °C measured, respectively, in both cylinders. The effect of temperature on moisture profiles (Fig. 3) has an important impact on moisture diffusivity variations versus moisture content (Figs. 7 and 8). Moisture diffusivity varies from 7.5×10^{-11} to 3×10^{-11} m^2/s at 20 °C and from 5×10^{-11} to 1×10^{-11} m^2/s at 10 °C in the range of 9.2 to 2.5 kg water/kg DM.

Moisture diffusivity increases with the moisture content when measured on gels being dehydrated (Fig. 8). But, moisture diffusivity seems to be constant or to slightly increase with the decreasing of moisture content in the gels being re-hydrated (Fig. 7).

The observed variations of diffusivity depend on the initial moisture content and on the sorption or desorption mechanism. This could be attributed to the difference in the network organization of the gels which affects the moisture mobility.

Bruin and Luyben (1980) also showed that diffusivity depends mainly on water content whatever the substrate. The shape of the curves of $D_i=f\ (X_i)$ in gel 1 (corresponding to moisture loss) (Fig. 8) are similar to those obtained by Ruiz Cabrera (1999) using moisture profiles obtained by magnetic resonance imaging (MRI) in gelatin gels during drying.

A study of sensitivity on the parameters used for fitting the moisture profiles was also performed. Fig. 9 shows the moisture diffusivity, in gel being dehydrated, calculated for a variation of ±10% of the identified coefficients A and B. The variations of moisture diffusivity due to the variations of these coefficients used for fitting the moisture profiles (Fig. 9) are smaller than the variations due to the temperature (10 or 20 °C) (Fig. 7).

The method used for calculating the diffusivity cannot be used for moisture contents too close to the constant values of the ends of the cylinders, when areas tend towards zero and slopes towards ∝. In fact, the areas and mainly the slopes used to calculate diffusivity, strongly vary in the range of moisture contents from 5.4 to 5.5 kg water/kg DM in gel 1 (Fig. 10) and in the range from 2.7 to 2.5 kg water/kg DM in gel 2 (when

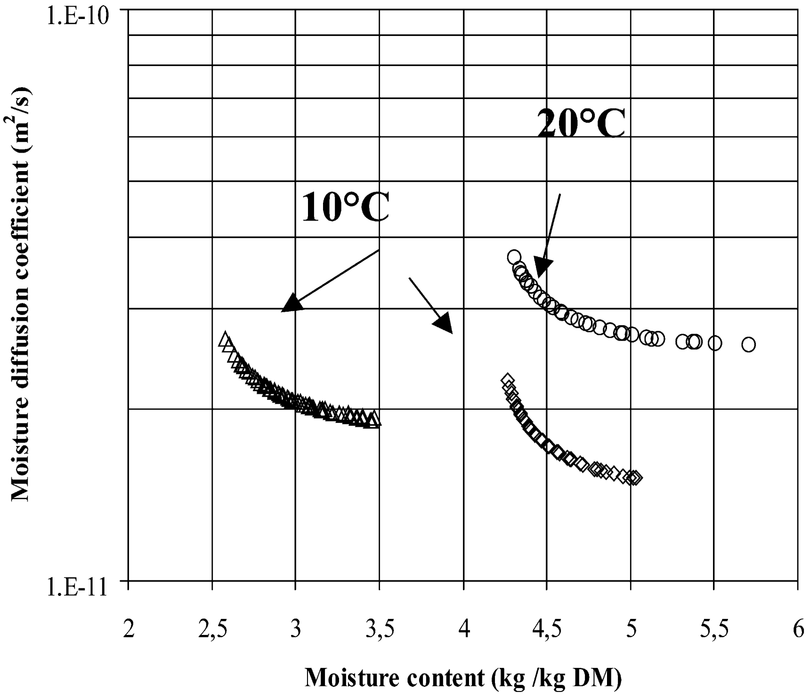

Fig. 7. Variation of moisture diffusion coefficient versus moisture content at 10 and 20 °C in gels of gelatin (gel 2: moisture uptake).

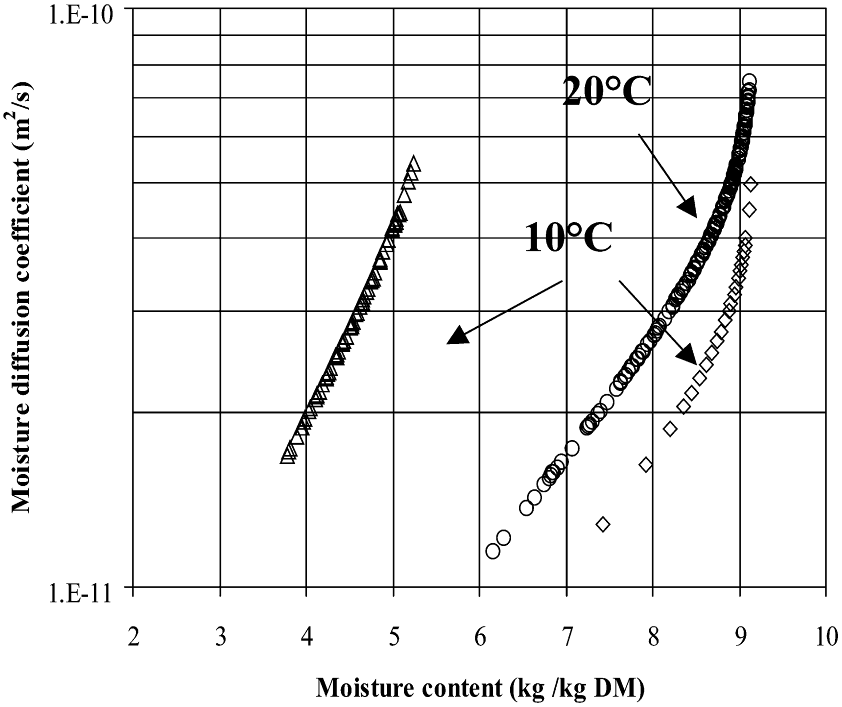

Fig. 8. Variation of moisture diffusion coefficient versus moisture content at 10 and 20 °C in gels of gelatin (gel 1: moisture loss).

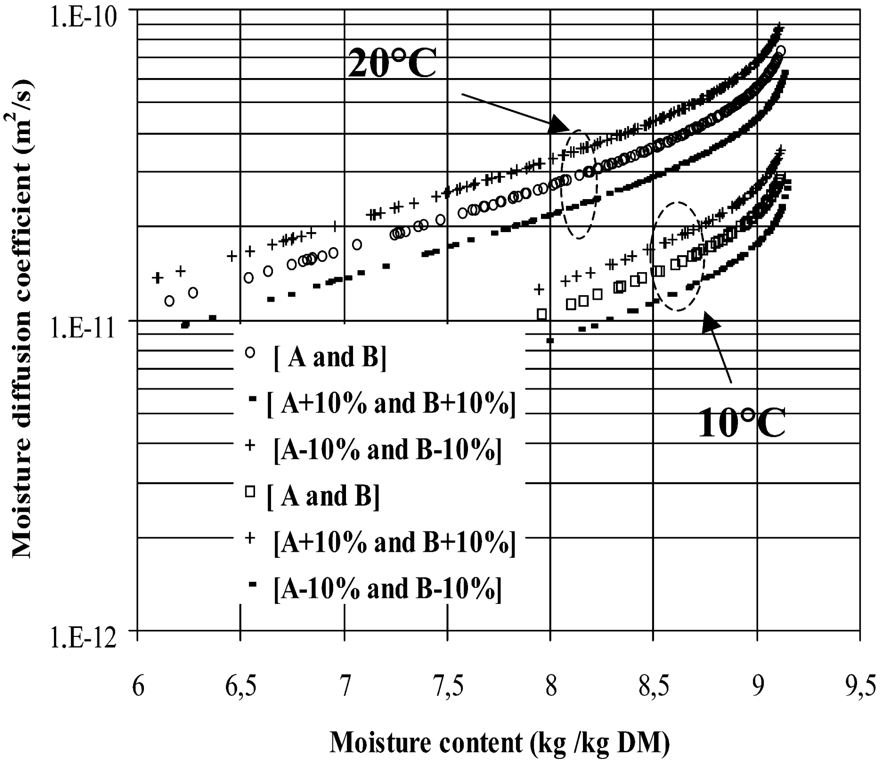

Fig. 9. Effect of the variation of the identified coefficients of fitting function on the moisture diffusion coefficient (20 °C).

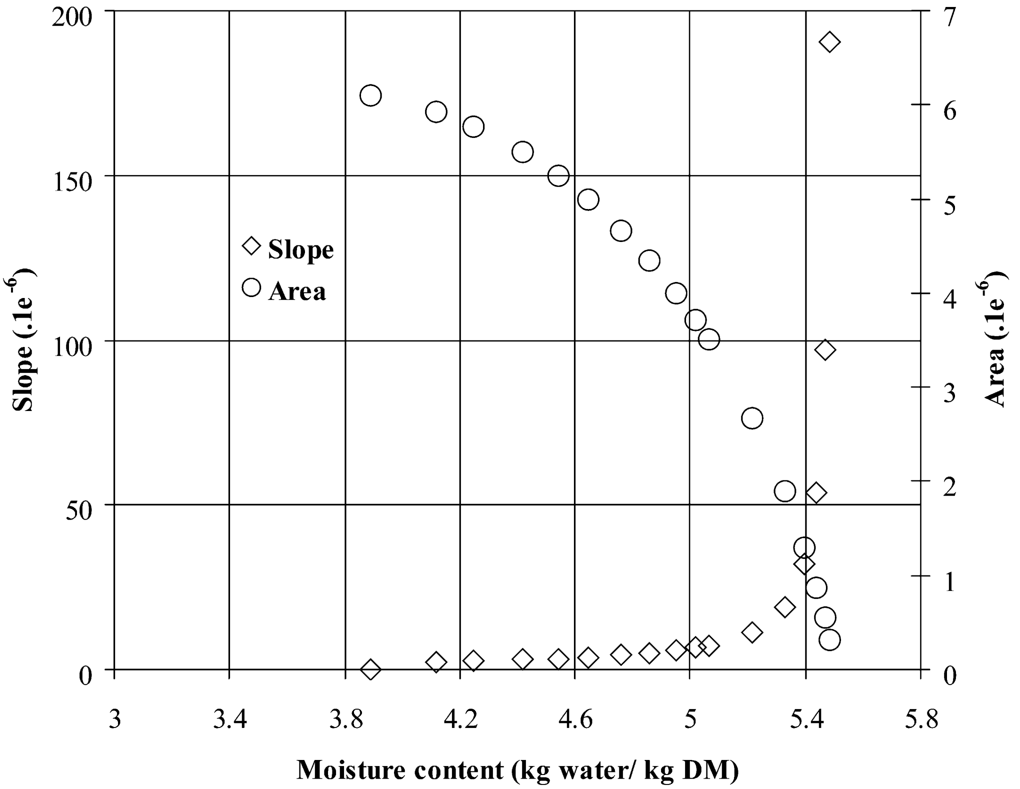

Fig. 10. Variation of the slope and of the area used to calculate moisture diffusivity (in gel 1).

$X_i \to X_0$). The determination of moisture diffusivity by this method becomes mathematically impossible when $X_i \to X_0$ $\left(\left[\frac{\partial\eta}{\partial X}|_{X=X_{i1}} \to \infty\right] \times \left[\int_{X_{01}}^{X_{i1}} \eta_{1i}\partial X_{i1} \to 0\right]\right)$. The values of moisture diffusivities obtained for those moisture contents close to initial moisture contents were not retained.

This method allows estimation of the moisture diffusivity in the range of large moisture contents. The advantage of this method is to allow the study of the variation of $D_i = f(X_i)$ and of the sensitivity of this variation according to the experimental conditions.

4. Conclusion

This study allowed estimation of moisture diffusivity for different gel compositions and experimental conditions (temperature of 10 and 20 °C and initial difference in moisture content of 3, 5 and 10%). Time-dependent water concentration profiles were obtained using a diffusion cell. Repeatable profiles were obtained for different conditions.

Moisture diffusivity varies from 7.5×10^{-11} to 3×10^{-11} m^2/s in the range of 9.1 to 4.3 kg water/kg DM in gelatin and starch gelatin gels at 20 °C and from 5×10^{-11} to 1×10^{-11} m^2/s in the range of 5.4 to 2.5 kg water/kg DM in gelatin gels at 10 °C. The matrix composition (gelatin or starch–gelatin gels) is found to have no significant effect on the rates of moisture transfer in the range of studied variations.

Moisture diffusivity increases with the moisture content for gels being dehydrated and seems to be constant or to increase slightly with decreasing moisture content in gels being re-hydrated. This could be attributed to the difference in the network organization of the gels. This method gives satisfactory estimation of moisture diffusivity in a large range of moisture contents; some precautions must be taken with mathematical form of the solution for values close to the constant moisture contents of the cylinder ends.

The advantage of the present method is to allow the study of the variation of $D_i = f(X_i)$ without any a priori form of the *f* function. Only small moisture fluxes were generated under those experimental conditions (10^{-6} to 10^{-7} kg of water /m^2s).

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