SHAPE EVOLUTION AND SHRINKAGE OF A GEL SYSTEM DURING DRYING BY FORCED CONVECTION

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Abstract: Knowledge of the shape evolution and shrinkage of a spherical gel system during drying significantly enhances the understanding of this process in the vision of the transport phenomena. This work consists in the development of a two components gel system, with spherical geometry, which allows to analyze the effect of the fluid flow, in the boundary layer, on the moisture transport, shrinkage and on the shape evolution of the sample, during drying in an air stream forced convection equipment. The shrinkage was observed through the capture of images, used for the calculation of shape factors. The process was evaluated under a laminar flow (based on particle diameter), with a agar concentration of 1.5 and 3%, fluid velocities varying from 0.8 to 2.0 m/s and particle diameters of $1.61.10^{-2}$ and $2.66.10^{-2}$ m, being the temperature maintained at 50 ^{0}C. The results confirmed with good reproducibility, proved statistically, that the circularity and specific mass of the samples decrease according to the formation of accentuated two-dimensional moisture profiles, for moisture content lower than the critical value, and, during the constant drying rate period, the analysis is concentrated in relation to the moisture transport, with the circularity and specific mass of the samples staying approximately constant. The gel system used allowed to reach the proposed objective, in a selective way, representing materials intensely affected by the shrinkage.

Keywords: sphere, gel, drying, forced convection, shrinkage, shape factors.

1. Introduction

Under the optics of the engineering of systems, the constant development of the drying processes is a goal that cannot be reached without the perfect understanding and, eventually, some domain of all the involved sub processes, as the shrinkage of the structure and the internal and external heat and mass transfer, present during the drying of countless materials, which determine the acting of the process on the physical integrity of the final product.

One of the main reasons for this quality loss is due to structural changes caused by the shrinkage of the product during the drying processes. The shrinkage promotes loss in the permeability characteristics to the solvent and turns the material unstable and brittle, both undesirable effects. Different attributes of quality of the dehydrated products, such as density, crust formation, cracks and others are all related with the contraction process (Achanta & Okos, 1996).

The gels are structures that suffer a considerable shrinkage during drying, because they have similar characteristics to materials undergoing shrinkage, due to the polymeric structure, reason why they are considered as simulators materials for drying studies. The gels systems as simulators are used mainly to simplify complex systems, with the objective of studying the factors which affect the quality of the products in a selective way, eliminating others that are not under investigation (Gogus & Lamb, 1998).

The gels have been used broadly as simulators in researches, as in the works of Gogus & Lamb (1998), Garcia & Bueno (1998); Roques et all (1994); Eichler et all (1997); Shah & Porter (1973), Mrani et all (1997), Moreira & Sartori (2000) and Castilho, Braun & Sartori (2002).

In these works several gels are used as starch gel, agar gel and others, for the study of chemical reactions, shrinkage mechanisms and the great majority in drying studies, involving the mathematical modeling based on balance equations of heat and mass transfer, considering the shrinkage of the system (moving neighborhoods), having as answers the influence of the process on the moisture profiles inside the materials, current deformations from the shrinkage, optimization of combined energy processes, among others. The agar gel, in matter, has been mentioned in the literature as a food simulator (Gogus & Lamb, 1998; Schrader & Litchfield, 1992) presenting some shrinkage characteristics during drying which are the same characteristics presented by certain vegetables, existing the possibility of application of agar gel systems, to describe transformations due to shrinkage, with the advantage of being constituted by only two components: water and polymer.

Many of the scientific studies of drying treat the mathematical modeling including the phenomenon of the shrinkage, however in a simplified way, considering the one-dimensional moisture diffusion. In samples with spherical geometry, these phenomena are considered in only one space dimension (the radial coordinate). These mathematical models may be reasonable to describe drying rates depending on the physical characteristics of the sample and conditions of the process, but are unable to predict the shape evolution and the physical deterioration.

It is still observed, in the literature, that little attention is given to the external phenomena emerging from the interaction among fluid and particle. This interaction causes alterations in the convective mass transfer coefficient, consequently, leading to a non uniform drying, with a greater physical deterioration of the products. These phenomena can be seen for a steady and uniform fluid flow around a sphere, immersed in a flowing medium (Geankoplis, 1978).

At Reynolds numbers (based on particle diameter) greater than 20, the transfer rates over the forward surface of the sphere are different and independent from those at the rear hemisphere, because the fluid-dynamic boundary layer, which is formed at the forward hemisphere, gets separated from the surface and a reverse flow is immediately established at the rear region, with the development of a second boundary layer.

The variations of these transfer rates in the boundary layer have great influence in the convective drying of materials which suffer shrinkage due to the moisture transport, because the two-dimensional moisture profiles will bring consequent shape evolution and physical deterioration, due to the appearance of stresses and internal torque inside the structure. A consideration of these effects, when using spherical samples, meet good opportunities for the mathematical modeling of the drying process, even to predict drying rates and further more, to predict the shape evolution of the materials undergoing shrinkage.

In this paper, the main objective consists in the development of a gel system, with spherical geometry, which allows analyzing the effect of the fluid flow, in the boundary layer, on the moisture transport, shrinkage and on the shape evolution of the spherical sample, during drying by forced convection.

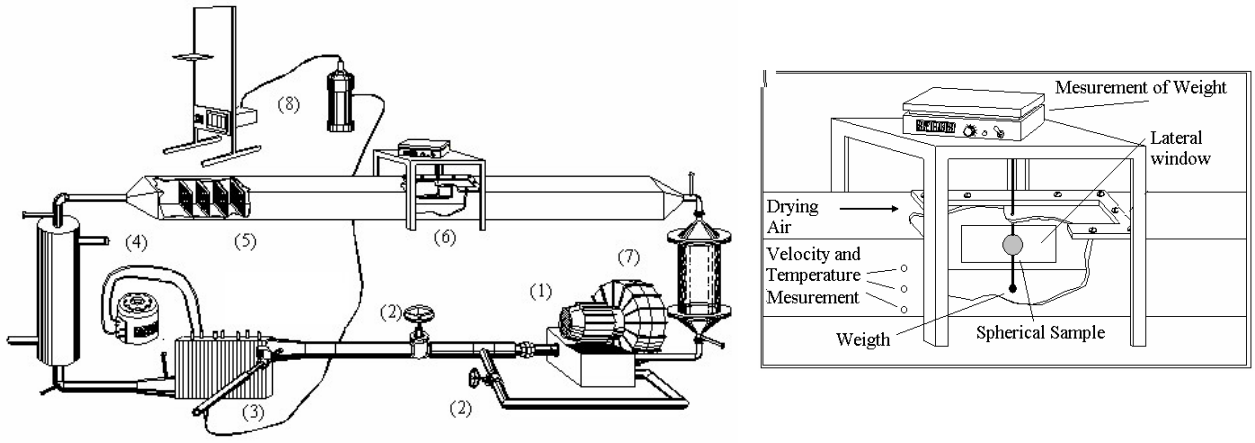
2. Materials and methods

2.1. Materials

Polymeric components as agar, microcrystalline cellulose, and starch were used to elaborate the gel system more appropriated for the study, and the tested compositions were based on works as the ones of Shash & Porter (1973), Schrader & Litchfield (1992), Gogus & Lamb (1998), Moreira & Sartori (2000) and Castilho, Braun & Sartori (2002). Metileno blue was used as coloring to obtain the necessary contrast in the subsequent analysis of images.

2.2. Equipment and experimental apparatus

The drying tests were accomplished in a dryer of forced convection with recycle of air, installed in agreement with the outline shown in Fig. (1.a) The unit is constituted by a blower type radial compressor (1), two valves (2), electric heater connected to a voltage regulator (3), double tube heat exchanger (4), drying compartment (5), lifting and weighting system (6), dryer of air (7) and a circuit for measurements of wet and dry bulb temperatures (8).



(a) (b)

Figure 1: (a) Idealized drying unit for the accomplishment of the experiments. (b) Outline for the drying of the samples by the continuous method.

The dryer was developed by Cassandre et all (2001), and it assists to the specific and fundamental needs for the drying process of this type of material, such as, it guarantees 98.7 % of uniform distributions of speed and temperature of the air, from 0.5 to 1.8 m/s and from 30 to 70 ºC, respectively, in the central region where the drying of the samples was processed, besides circulation of the air through an air dryer and heat exchanger, keeping the relative humidity and the temperature of the air in approximately constant values, through adjustments in the components of the unit.

The capture of images during the process was accomplished through a lateral window. The sample to be dried was suspended in the drying air by a cotton thread with $1x10^{-3}$ m of thickness, connected to the scale, for direct measurement of mass. This form of capture of images and mass registration was called the continuous method, and the outline consists in Fig. (1.b)

For the second form of image capture and mass registration along the process, a acrylic platform was used with an area of $2.5.10^{-3}$ m^2, connected to a stem of metal with 2.10^{-3} m of diameter, being the sample fixed to the stem, and the platform retired from the equipment in established time intervals, for the acquisition of data, and placed into the same after. This procedure corresponds to the intermittent method of acquisition of data.

The two methods of acquisition of data were appraised by the reproducibility of data, which was proven statistically, making possible the decision for one of the two methods for the conduction of the experiences.

2.3. Determination of the process variables.

For measurements of the drying air temperature and speed, T_A and V_A, respectively, a digital thermo-anemometer was used (ALNOR, model 8525), precision of 0,1 m/s for the speed and 1°C for the temperature, taken near the previous area of the samples. The mass of the sample was measured through a scale of the mark GEHAKA, model BG 440, precision of 10^{-6} kg.

To verify the initial dimensions of the samples a caliper, mark SOMET INOX, was used, precision of 5.10^{-5} m. measured. For measurement of relative humidity thermal-couples of wet bulb and dry bulb were used (copper-constantan) with the precision of 0.25 ^{0}C for the temperature and 4% for the relative humidity.

The shrinkage was registered along the process through a digital photographic camera, CÁSSIO, model LK 10V. The images obtained with the digital camera were analyzed in the program IMAGE FOR PLUS®[1], for the obtaining of data as projected area, projected perimeter, larger diameter, smaller diameter and medium diameter.

The determination of the moisture of the samples was accomplished according to the method of Lees (1980). The method was used for the determination of the mass of dry solid of the sample, after the drying experiments, information necessary for moisture calculations (dry basis).

®[1] Media Cybernetics, Inc.

2.4. Preparation of the samples and drying tests

The selection of a gel system simulator, according to Van Arsdel (1973), is based on the minimization of phenomena other than those under investigation. For this work, the main concern was the selection of a gel system, which develops shrinkage and shape evolution, according to the two-dimensional moisture transport, caused by the different coefficients of mass transfer by convection in the previous and subsequent areas of the sphere. This behavior corresponds to materials with high initial moisture content (around 95%).

Was also considered the composition which allows the molding and extraction of the samples, in spherical geometry, without the formation of ruptures previous to the drying process. The concentrations studied were in a range from 1 to 3%, for agar, 1 to 7% for starch and 1 to 9% for microcrystalline cellulose, being the range of concentration values tested based on available results in (Gogus & Lamb, 1998), Moreira & Sartori (2000) and Castilho, Braum & Sartori (2002), being chosen the agar as the only solid component, as justified in the results.

Agar, was weighed and mixed with water according to the method described in Food Chemical Codex (1980), being obtained a clear liquid, which solidifies between 32 and 39 ^{0}C, forming a firm and resistant gel which is not liquefied below 85 ^{0}C. The hot solution was then spilled in brass molds, with dimensions of $1.61.10^{-2}$ and $2.56.10^{-2}$ m of diameter and with initial circularity $\phi = 1$.

After the mass measurement of the gel samples, they were led individually for the drying operation, where the equipment was already in steady state, with the variables temperature and speed of the air kept in the established values. The end of the drying operation was when the mass of the sample became constant along the drying time.

2.5. Experimental conditions

Experiments were performed to evaluate the influence of the initial diameter of the samples, (D_0), with values of $2.660.10^{-2}$ and $1.610.10^{-2}$ m and the influence of the drying air speed, (V_A), varying from 0.8 to 2.0 m/s, being the temperature of the drying air on the samples, (T_A), maintained in 50 ^{0}C ($\pm$ 1 ^{0}C). This range of values was chosen to guarantee a laminar flow (based on the particle diameter), to avoid long drying periods and to minimize the influence of the walls of the tunnel in the air flow on the samples.

The initial concentration of agar (in wet basis), was 3 and 1.5%. Agar was the component selected to compose the gel system in this study. Preliminary experiments, accomplished by the two methods of acquisition of data (intermittent and continuous) were replicated to evaluate the reproducibility.

2.6. Treatment of data

2.6.1. Determination of the shape of the particles

Wadell (1933), apud Clift et all (1978), introduced the "circularity" degree (ϕ), dimensionless parameter. Unlike the sphericity, which consists of a relationship among superficial areas, the circularity degree ϕ, can be determined by photographic observation, through the projected area and the projected perimeter of the sample, according to Eq. (1).

$$\phi = \frac{P_{ES}}{P_P} = \delta \frac{D_{ES}}{P_P} \qquad (1)$$

Where P_{ES} is the perimeter of the projected area equivalent sphere, P_P the projected perimeter of the sample and D_{ES} the diameter of the projected area equivalent sphere. The projected perimeter and projected area are obtained through the analysis of images, and the circularity (¢) calculated is used to evaluate the shape evolution of the sample during the process.

Was also evaluated the ratio between the difference of the maximum and minimum diameters and the medium diameter, measured through the analysis of images, according to Eq. (2). The ratio D_F represents the difference among the shrinkage of the sample in the area previous to the separation of the flow and the shrinkage in the subsequent area, due to the different coefficients of mass transfer by convection in the boundary layer.

$$D_F = \frac{D_{MX} - D_{MN}}{D_{AV}} \tag{2}$$

Where D_{MX} is the maximum diameter, D_{MN} the minimum diameter and D_{AV} the medium diameter.

2.6.2. Equations for the volume and the specific mass

In order to adjust the linear dependence of the volume with the moisture, an equation was used for the shrinkage, in agreement with Iglesias et all (1993) and Roques et.all (1993). The physical meaning of this equation for linear shrinkage is that all the contraction suffered by the agar gel sample is equal to the volume of water evaporated of its structure.

$$V_g = Vs + V_w \tag{3}$$

$$\varepsilon = (\rho_s/\rho_W) \tag{4}$$

$$V_g = Vs\ (1+\varepsilon X_{DB}) \tag{5}$$

Where V_g is the volume of the gel, V_S the volume of the solid, V_W the volume of water, $\rho_{s,}$ the specific mass of the solid, ρ_W the specific mass of the water, X_{DB} ,the average moisture (dry basis) and ε the coefficient of linear shrinkage. In Eq. (4), ε is the same to the relative specific mass of the agar. X_{DB} is defined as the total water of the sample divided by the mass of dried solid. Relating Eq. (3), (4) and (5), we have Eq. (6) for the volume of the gel:

$$V_g = (m_s / \rho_s).(1+Xbs.(\rho_s / \rho_W)) \tag{6}$$

Where, m_s, is the solid mass. Starting from the Eq. (6) for the volume it is obtained the equation for the specific mass of the gel, ρ_g, Eq. (7):

$$\rho_g = (m_s + X_{DB}.m_s)/((m_s / \rho_s).(1+X_{DB}.(\rho_s / \rho_W))) \tag{7}$$

Equation (6) was used to verify if the data of equivalent volume, V_{EQ}, were adjusted to the model of linear shrinkage. V_{EQ} corresponds to the volume of the sphere with same projected area, measured experimentally. Equation (7) was used to compare the specific mass of the gel, described by the linear shrinkage model, with the specific mass of the sample, calculated from the experimental data, according to Eq. (8).

$$\rho_{Sa} = (m_{Sa} / V_{EQ}) \tag{8}$$

Where ρ_{Sa}, is the apparent specific mass of the sample and m_{Sa} is the mass of the sample, measured experimentally.

2.6.3. Evaluation of the adjustment of linear shrinkage model and reproducibility

With data of V_{EQ} and V_g, for each experiment, a linear regression was made, through Eqs. (9) and (10)

$$V_{EQ} = a\ V_g \tag{9}$$

$$a = 1 \tag{10}$$

The adjustment is verified by the parameter a close of 1, insured statistically from the explained variance, standard deviation and t-test. The same procedure was used to verify the reproducibility, being V_{EQ} and V_g substituted by replicated values.

2.6.4. Determination of mass effective diffusivity and mass Biot number

For the experiments was determined the drying constant, K, through an non linear estimation, being used the exponential law, Eq. (11), in the integrated form, with two parameters, correlation which establishes that the drying rate is proportional to the free water concentration of the material, in agreement with Pinto & Tobinaga, (1996).

$$X = \left(\frac{X_{DB} - X_{DBe}}{X_{DB0} - XDBe} \right) = A \cdot \exp(-K \cdot t) \tag{11}$$

Where X is the dimensionless moisture, X_{DBe} the dynamic equilibrium moisture (dry basis), which corresponds to the moisture of the sample when the mass becomes constant in the end of the experiments, X_{DB0} the initial average moisture (dry basis), A a dimensionless parameter and t the time.

This equation corresponds to the first term of the series which is the solution of the fickan model, where for long drying times, only the first term is significant. Starting from the drying constant, it can be determined the effective diffusivity, through the relationship for spheres, Eq. (12), from the fickian model, in spherical geometry.

$$K = \frac{\delta^2 \cdot D_{EFF}}{r_{X_{DB}}^{\ 2}} \tag{12}$$

Where, $r_{X_{DB}}$ it is the ray as a function of the average moisture.

The mass Biot number (Bi_m) is calculated in agreement with HERNÁNDEZ et al. (2000), that follow CRANCK (1975), redrafting mass Biot number in the following way:

$$Bi_m = \frac{K_c \rho_{air} x_1 K_{eq}}{\rho_s D_{EFF}}, \tag{13}$$

Where x_1 is the characteristic dimension, K_c is the coefficient of mass transfer by convection, ρ_{air} is the specific mass of the dry air and Keq represents a constant of medium partition:

$$Y_i = K_{eq} X_i \tag{14}$$

Being Yi substituted by the absolute humidity of the drying air (Y) and Xi for the equilibrium dynamic moisture of the sample (X_{DBe}).

The coefficient of mass transfer by convection, Kc, is obtained by the analogy with the transfer of heat, and, the medium Nusselt number, according to WHITAKER (1972), which proposed an equation valid for liquids and gases draining on spheres.

2.6.5. Drying kinetics

The data of drying kinetics were treated through Curves of mass flux, according to Eq. (15), using -the programs ORIGIN®[2]and STATISTICS®[3], and the moisture of the sample along the process expressed in dry basis.

$$R = -M_{DS} \frac{\frac{d(X_{DB})}{dt}}{A_{ES}} \tag{15}$$

Where, $\frac{d(X_{DB})}{dt}$ is the drying rate, X_{DB} the average moisture (dry basis), M_{DS} the dried solid mass, A_{ES} the area of the equivalent sphere and R the mass flux.

®[2] Micro cal Software, Inc. ®[3] StatSoft, Inc.

3. Results and discussions

3.1. Selection of the gel system

Gel systems were elaborated and submitted to the drying process, according to the compositions and concentrations presented in the methodology. The gel systems elaborated with starch, microcrystalline cellulose and agar presented a reduction in the shrinkage and became hollow in the initial stages of the drying. The microcrystalline cellulose addition in larger proportions reduced the formation of the central cavity, but the circularity of the sample didn't change during the process.

The samples composed just of agar as solid component, in the concentrations of 1.5 and 3% (wet basis), also presented the central cavity in the period of decreasing drying rate, but it was possible to analyze the effect of the moisture transport on the shrinkage. This composition was chosen because the agar gel shrinks more strongly in the area previous to the separation of the flow, allowing relating the changes in the shape factors studied, with the mass transfer.

The two levels of concentration of agar used, 1.5 and 3%, allowed to observe the changes in the shape factors and specific mass of the samples, but the level of agar concentration of 3% reduced the adherence of the sample on the stem of the platform.

These observations are in agreement with available results in Gogus & Lamb (1998), and they were used as criteria for the selection of agar as solid component for the gel system.

3.2. Model for the shrinkage

In Fig. (2) is had typical results of the adjustment of the experimental data to the model of linear shrinkage, Eq. (6).

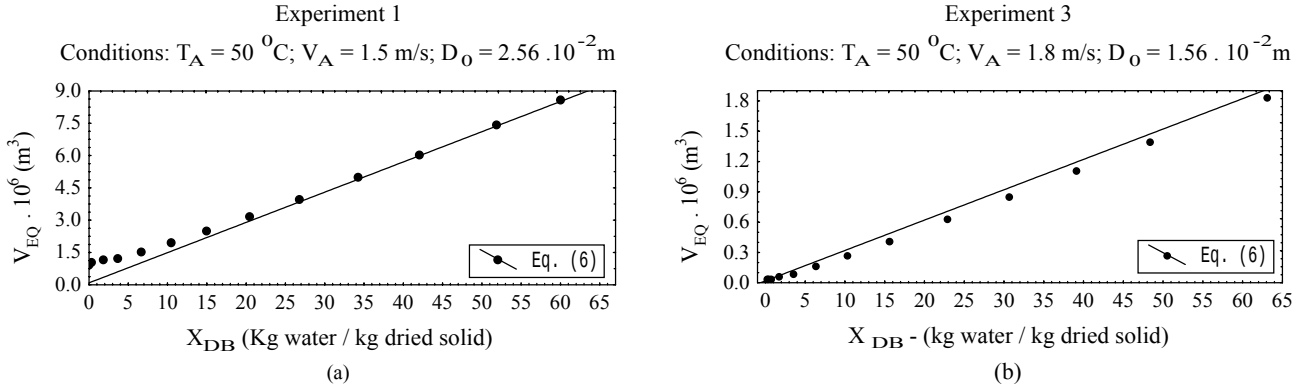


Figure 2: V_{EQ} as a function of X_{DB}. (a) Continuous method. (b) Intermittent method.

For the experiments of Fig (2) a concentration of agar of 1.5% was used and for the others experiments the concentration of 3%. In the experiment of Fig. (2.a) the capture of images and the measurement of the mass of the sample were accomplished by the continuous method, and for the experiment of Fig. (2.b) by the intermittent method. A good agreement is had between the experimental data and the model of linear shrinkage, for the experiment of Fig. (2.b), accomplished by the intermittent method, insured for the coefficient of correlation greater than 0.99 and the parameter a = 0.929.

However, for the experiment of Fig. (2.a), the points stand back of the model for values of X_{DB} less than 10. This can be explained by the fact that the gel stuck to the thread to which it was suspended in the dryer, and the accountancy of the stuck volume carted in an experimental error in the measurement of projected area, as it can be observed by the value of the correlation coefficient, r, in Tab. (1), for the experiment 1 and replicate.

Table 1: Statistical parameters of the linear regression of V_{EQ} with Eq. (6), for typical replicated experiments.

Experiment	Parameter a (dimensionless)	Standard desviation	T-test	Correlation coefficient	Variance explained (%)	P Value	Significance level
1	1.033	0.037	28.103	0.978	95.611	< 0.001	0.050
1 (replicate)	0.840	0.028	29.767	0.979	95.796	< 0.001	0.050
3	0.929	0.0087	106.73	0.999	99.80	< 0.001	0.050
3 (replicate)	0.935	0.0097	96.48	0.999	99.77	< 0.001	0.050

The method of measurement of the shrinkage for the experiment of Fig (2.b) doesn't measure this stuck volume and the points are adjusted better to the model of linear shrinkage, along all the process, proven for the coefficient of linear

correlation greater than 0.99 in Tab. (1). however the points locate below the model, due to the fact that the stuck volume was not counted.

Experiment of Fig. (2.b) was replicated, being verified the reproducibility of the moisture, projected area and projected perimeter data, according to Eqs. (9) and (10), with the parameter a ≅ 1 and the coefficient of correlation greater than 0,99.

Experiment of Fig. (2.a) was also replicated, however only the reproducibility of the moisture data was verified, with the parameter a ≅ 1 and the coefficient of correlation greater than 0.99, however for the area and projected perimeter data, the parameter a was different from 1 and the coefficient of correlation smaller than 0.99, not being verified the reproducibility.

Finally, Eq. (6) was considered to represent the shrinkage of the gel system studied and the intermittent method of acquisition of data was selected, for the analysis of the drying kinetics and shape evolution of the sample.

3.3. Drying kinetics and shape evolution of the samples

3.3.1 Circularity (¢)

In Fig. (3), is had the mass flux and circularity (¢), as a function of the moisture (dry basis), where it is possible to do a comparison between the drying periods and the shape factor circularity, for two typical experiments.

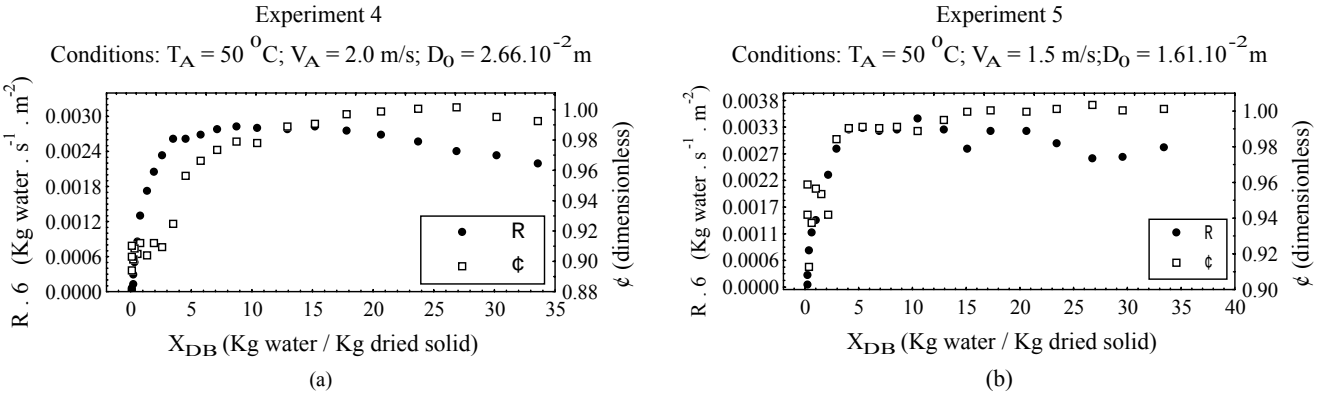


Figure 3: R and ¢ as a function of X_{DB}.

The general observation was that ¢ came approximately constant during the period of constant mass flux, decreasing strongly for moisture contents below the critical value, which is about 5 (Kg water / Kg dry solid), for experiments 4 and 5, Fig. (3).

This dependence can be explained by the fact that during the period of constant mass flux, the analysis is concentrated in relation to the moisture transport, without the formation of two-dimensional moisture profiles. For moisture contents below the critical value, a decreasing ¢ is had, with the shape degradation of the samples developing according to the formation of two-dimensional moisture profiles, in the period of decreasing mass flux.

It could also be observed, in all the experiments, the development of a superficial fissure, on the subsequent area of the sphere, according to the decrease of the circularity. The location of this fissure is an important observation, because it evidences that the external layers, of the previous area to the separation of the flow, reach the local moisture for the vitreous transition before the layers of the subsequent area, generating tensions in the structure of the gel system and the breaking in the subsequent point of stagnation, where highest moisture is had and, consequently, smaller mechanical resistance of the sample. It was understood that the shape evolution of this superficial fissure, during the process, is related with the decrease of ¢ in the period of decreasing mass flux.

The formation of two-dimensional moisture profiles can be explained by the separation of the flow in the boundary layer between the solid and the fluid, which causes greater coefficients of mass transfer by convection, on the area previous to the flow separation, in comparison with the subsequent area. The formation of two-dimensional moisture profiles promotes internal tensions in the structure of the gel system, for moisture contents below the critical value, as described by Mrani et all (1997).

It is still observed in Fig. (3) that the sample of greater V_A and D_0, presents a decrease in the circularity for superior moisture contents, when compared with the sample with smaller V_A and D_0, due to the increase in flow separation effect on the coefficients of mass transfer by convection, on the previous and subsequent areas of the gel system.

It was verified that circularity is an important shape factor which allows evaluating in what period of the process the sample begins to deteriorate.

3.3.2. Specific mass (ρ_{As})

In Fig. (4) is had the mass flux and specific mass of the sample, calculated with the experimental data, and the model for the specific mass of the gel, Eq. (7), all of them as a function of the moisture in dry basis.

The important observation is that ρ_{As} , in a similar way to circularity, decreases for moisture contents below the critical value of 5 (kg water / dry solid kg), in contradiction with Eq. (7), that explain a specific mass approximately constant, during the period of constant mass flux, and an increase for moisture contents below the critical value, reaching values close to the specific mass of the solid agar (1551 kg / m3).

This decrease in the apparent specific mass, in the period of decreasing mass flux, can be explained, by the development of the fissure into the structure of the sample, which promotes porosity, as observed, cutting the samples in the end of the experiments and being verified that they were hollow.

The development of this internal fissure can be explained, by the extinction of the shrinkage on the superficial layers of the previous and subsequent areas of the sample. As the inside of the sample continues to shrink, with the moisture transport, due to not having reached the vitreous transition, a breaking appears inside the sample.

The porosity, evidenced by the decrease in apparent specific mass of the sample, is also a parameter of quality loss during the process, developing as a function of moisture profiles.

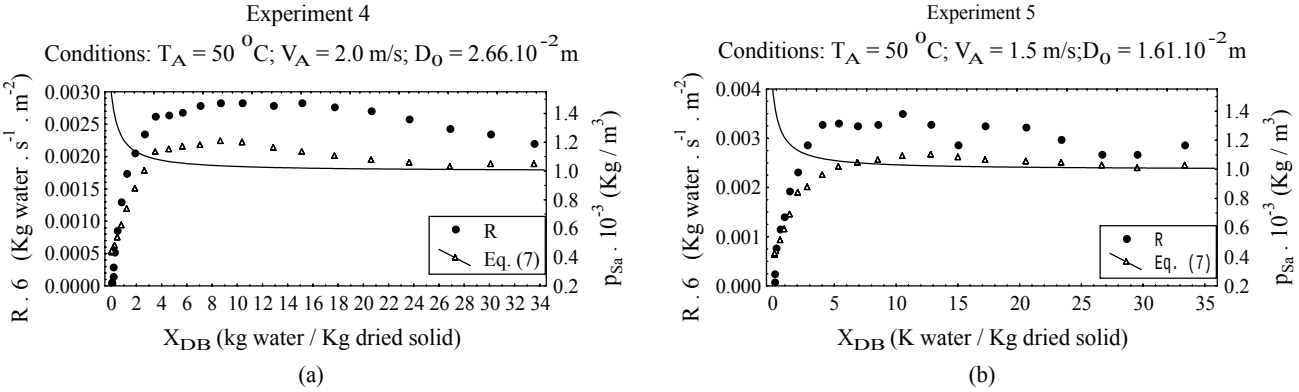


Figure 4: R and specific mass of the sample (obtained from the experimental data and from the model of ideal shrinkage) as a function of X_{DB}.

3.3.3. Relationship of diameters (D_F)

Another possibility to analyze the influence of flow separation on the drying and shrinkage is through the relationship D_F, as it can be observed in Fig. (5). The relationship among the diameters increases during the period of constant max flux, due to the drag force, and in the initial phase of the decreasing mass flux period due to the difference among the coefficients of mass transfer by convection, for the previous and subsequent areas of the sphere. However, when reaching the second phase of the decreasing mass flux period, this relationship begins to decrease. This behavior can be explained due to the fact that the previous area of the sphere reaches the vitreous transition before the subsequent area.

However D_F keeps until the end of the drying a high value, indicating that non uniform drying has happened during the process. Considering these observations, D_F is also an indicative number of quality deterioration of the samples.

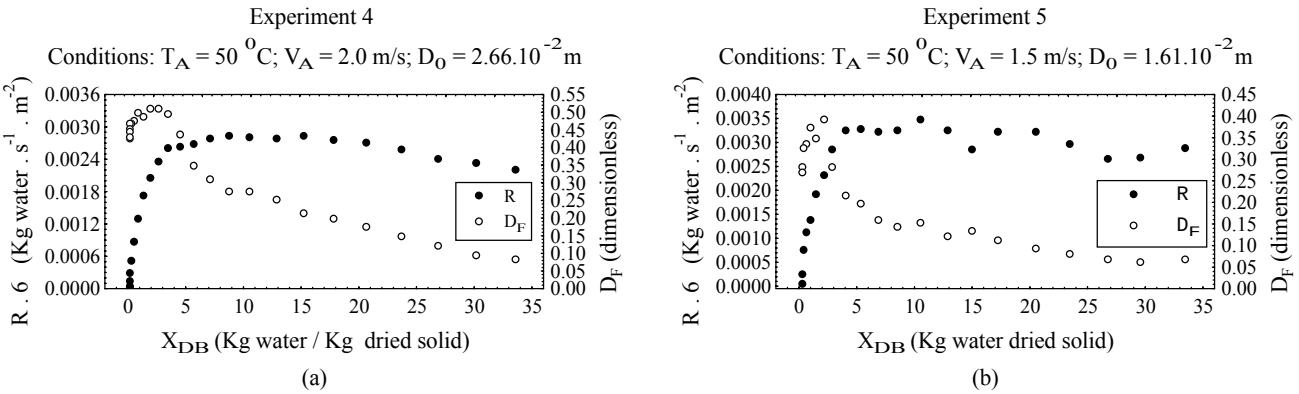


Figure 5: R and D_F, as a function of X_{DB}.

3.3.4. Mass Biot number

It can be observed, from Figs. (6.a) and (6.b), that during the period of constant mass flux, the mass biot number presents a small variation, in relation to the great amount of water that is removed from the material during this period, indicating that the resistance to the convective moisture transport is predominant, with values for Biot smaller than 30.

During the period of decreasing mass flux, an accentuated variation of the Biot number is had, in contrast to the small amount of moisture that is removed from the material in this period, and Biot overcomes the value of 30 in the end of the process. This indicates that the resistance to the moisture diffusion inside the material increases strongly in the period of decreasing rate.

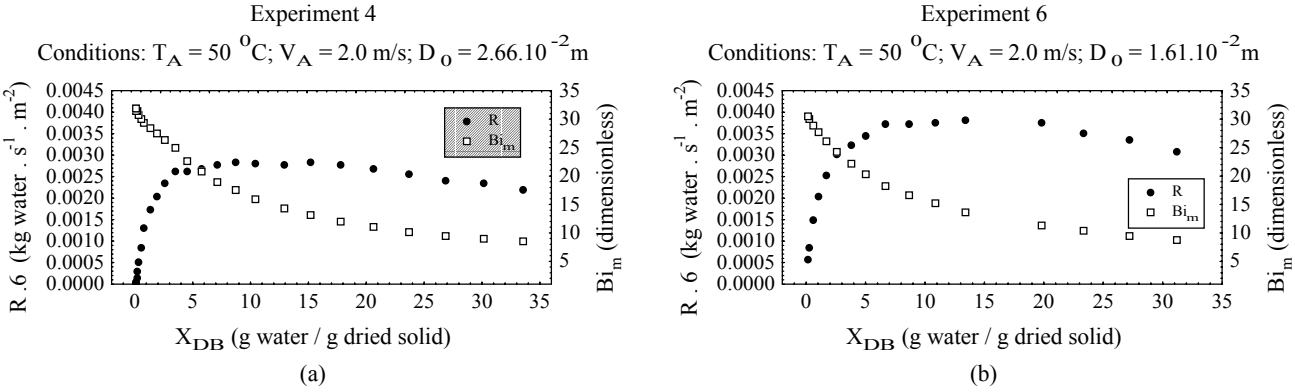


Figure 6:R and $Bi_{m,}$ as a function of X_{DB}.

According to HERNÁNDEZ et al. (2000), for a mass Biot number greater than 30, the resistance to the phenomenon of mass transfer by convection is despicable, in comparison with the resistance to the mass transfer by diffusion inside the material, characterizing the predominant diffusion process. The statements HERNÁNDEZ et al. (2000) are in agreement with what is observed starting from the Fig (6).

Through this verification, it can be inferred that the analysis is concentrated in relation to the moisture transport during the period of constant mass flux, without the occurrence of moisture profiles. But in the period of decreasing mass flux, it can be inferred that the resistance to the diffusion mechanism increases, hindering the moisture transport inside the material, what favors the formation of moisture profiles, being the analysis distributed.

These observations regarding the dependence of the mass Biot number, with relationship to the drying periods, are in agreement with the previous observations done about the decrease of the circularity and specific mass, and on the increase of the relationship of diameters, as well as, the relationship of these parameters with the drying periods and with the formation of moisture profiles.

The number of mass Biot is an important dimensionless number in the analysis of the process and it can be related with the shape evolution of the sample during the drying process by forced convection, combining the effects of the speed of the drying air, the dimension of the sample and effective diffusivity.

4. Conclusions

The linear shrinkage model was considered satisfactory to represent the shrinkage of the gel system, with small deviations in the period of decreasing mass flux. These deviations are due to experimental error in the measure of the shrinkage, because of the of gel degradation phenomena, in the period of decreasing mass flux.

The observations done regarding the behavior of the circularity, specific mass, relation of diameters and mass Biot number, evidenced the importance of considering the phenomenon of flow separation, in the boundary layer between the solid and the fluid, because of its influence on the drying kinetics, shrinkage and shape evolution of materials with spherical geometry and high contents of initial moisture, while the quality of the dehydrated products is a constant concern.

In addition, it was concluded that the gel system used allowed to analyze, in a selective way, the effect of the moisture transport, on the shrinkage and shape evolution of the samples, being used agar as only solid component, representing materials intensely affected by the phenomenon of the shrinkage, with moisture contents around 95% (wet basis).

The present work is an initial effort for a major task of modeling the process of drying by forced convection to simulate, not only the drying kinetics, moisture profiles and the shrinkage of the material, but also to foresee the shape evolution of the gel system, and the consequent degradation of its physical integrity, contributing in this way to the scientific evolution of the drying processes.

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