DRYING RATES IN SHRINKING MEDIUM: CASE STUDY OF BANANA

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Abstract - Drying of foodstuffs is used to improve product stability, but presents some potentially harmful side effects such as shrinkage. The reduction of the relative humidity of the environment was studied in this work to substitute heating during drying, also taking into account the effect on shrinkage. Drying experiments of cylindrical slices of banana were conducted in commercial equipment, with controlled temperature and relative humidity. The samples of banana, with diameter/thickness aspect ratio of approximately five, were used. Results showed the existence of a constant drying flux period is when the variation of the transfer area is taken into account, which is evidence that the shrinking is two-dimensional. Relative humidity, and not only temperature, influences the final characteristics of the product. With this, an equivalence project of drying rates is considered in different conditions for the optimization of energy costs and product quality.
Keywords: Glass transition; Case-hardening; Drying flux.

INTRODUCTION

Drying is a unit operation frequently used in the production of diverse materials as to improve storage and transport conditions. In both these applications, it is important to have a control of the physical properties of the dried material in order ascertain its quality, since removal of moisture can have deteriorating effects (Moropoulou et al., 2005).

During the drying process, deformable materials undergo volume deformations, usually referred to as shrinkage. If the shrinking during the drying were ideal, the volume reduction would be equivalent to the volume of the removed liquid water. Diverse works in literature make use of the hypothesis of ideal shrinking (see e.g. Waje et al., 2005).

However, there is experimental evidence that shrinkage extent during drying is strongly related to drying conditions (Mayor and Sereno, 2004). These relations are expressed in the forms of the glass transition temperature theory (Rahman, 2001,

Katekawa and Silva, 2007) and crust formation, also referred to as the case-hardening phenomenon (Ratti, 1995).

The first theory contemplates only the effect of the temperature of the material during the drying. As water possess a plasticizing effect in amorphous materials, the higher the moisture content the lower the glass transition temperature of the solid (Rahman, 2001). This way, the material may undergo transition from the rubbery to the glassy state and the lower the drying temperature, the quicker this transition occurs. As this transition restricts the volume reduction, lower drying temperatures lead to lower shrinkage extent values and in consequence higher material porosities.

The formation of the crust can occur during drying due to the formation of high moisture content gradients within the dried material. The dried surface reaches the glassy state first while the interior of the material still is moist and rubbery. This hard surface hinders not only volume reduction but also moisture

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removal. As drying progresses, material shrinking is restricted and the liquid water removed is replaced by air (pores), provided that the crust does not crack.

These two theories contemplate different situations. In a way, the theory of case-hardening may be considered a special case of the glass transition theory, when the drying rate needs to be incorporated as a qualitative criterion. Glass transition theory is valid when the moisture content and temperature gradients within the material are not strong enough to cause a partial phase transition. Due to the strong plasticizing effect of water, the material only undergoes transition in the end of drying. Crust formation, on the other hand, occurs as soon as the surface of the material reaches a moisture content value low enough, which can occur in the beginning of the drying process.

Therefore, the drying conditions are determinant on the physical characteristics of the dried material. The objective of this work is to study the effect of the temperature and relative humidity of the drying agent on the kinetics of drying and on the shrinking of the material during the process.

Drying Periods

The classic description of the drying process contemplates the existence of two distinct periods: the first period, when the surface of the material is saturated and the drying rate is constant, and the second period, when the internal diffusion is important and the drying rate decreases. Perré and May (2002) argue that the existence of the constant drying rate period is conditional on two restrictions: the surface pressure is equal to the saturation pressure and the transfer area is constant. Since during drying of deformable materials the second condition can not be satisfied, the constant rate period is not observed. The authors considered the reduction of the volume of the dried material and, consequently, the reduction of its area available for heat and mass transfer, and showed that the ratio between drying rate and this area remains constant during some time in the beginning of the drying process. This ratio, which is the definition of moisture mass flux, is dependent only on the external drying conditions. Thus, the description of the first drying period using the concept of constant mass flux is more adequate.

Banana

Bananas of variety *Musa acuminata*, *Cavendish* sub-group, or *Musa* AAA, were chosen as sample

due to the importance this fruit possess in Brazil and to the existence of some studies of drying with shrinking of this fruit available in literature (e.g. Queiroz, 1994; Boudhiroua et al., 2002; Talla et al., 2004). Banana is a tropical fruit consumed primarily soon after being harvested and Brazil is one of the world-wide leaders in its production and consumption (Nogueira and Park, 1992). In accordance with the Institute of Agricultural Economy of the State of São Paulo (IEA-SP), the production of bananas in the State of São Paulo in 2005 surpassed 1127 thousand tons, equivalent to 500 million "reais" (IEA, 2007). Over 70% of this amount comes from the Ribeira Valley region on the southern part of the state. According to the Ministry of Agriculture (MAPA, 2007), the State of São Paulo was responsible for 16% of the national production in 2005, which totaled 6997 thousand tons.

Drying of bananas is used not only for preservation, but also to aggregate value to the product, as in chips production (Demirel and Turhan, 2003) and "banana-passa" (Nogueira and Park, 1992).

EXPERIMENTAL

Banana fruits were acquired on the day prior to the experiments and kept cooled at 10ºC. In order to standardize the samples used, yellow greenish bananas with no black points were purchased from the supplier.

Bananas were washed and peeled manually. Cylindrical slices were prepared using a two-edge cutter with spacing of 4.02 ± 0.01 mm between edges and a cylindrical cutter of 19.939 ± 0.007 mm of diameter. The slices were always removed from the central part of the banana, since longitudinal variations in moisture content and density were observed within a specimen. Drying experiments were conducted in a commercial equipment, the Dynamic Vapor Sorption (DVS), presented schematically in Figure 1. This equipment promotes the gas flow around the sample, with controlled temperature, relative humidity and velocity. The values of temperature and relative humidity used in the experiments are specified in Table 1; these values were measured to a precision of 0.1ºC and 0.1%, respectively. The gas velocity was the same in all experiments, with an average value of 0.119 m/s. The dry gas used was nitrogen, with 99.9995% purity.

The criterion used for the selection of the experimental conditions presented in Table 1 was the

same value of absolute humidity of air in the three temperatures. For each experiment, one sample was used. The process was carried out until thermodynamic equilibrium, recording the values of sample mass, relative humidity and temperature each minute.

The initial and final volume and the apparent density were determined by weighing the samples in air and a liquid of known density, following procedure described by Lozano et al. (1980). The initial values of volume and density were determined from control samples from the same fruit that the dried sample. The final values were determined with

the dried sample. Transfer area of the sample was determined from experimental data of time evolutions of the volume, diameter and thickness of the sample during drying in an independent experiment. For this calculation sample was considered to keep its cylindrical shape during the process. After the drying experiments in DVS and the determination of the final volume, the samples were dried in a vacuum oven, at 70ºC for at least 24 hours, until reaching a constant mass, for the determination of the dry solids mass. These samples were used in dry mass true density determinations by Helium pycnometry.
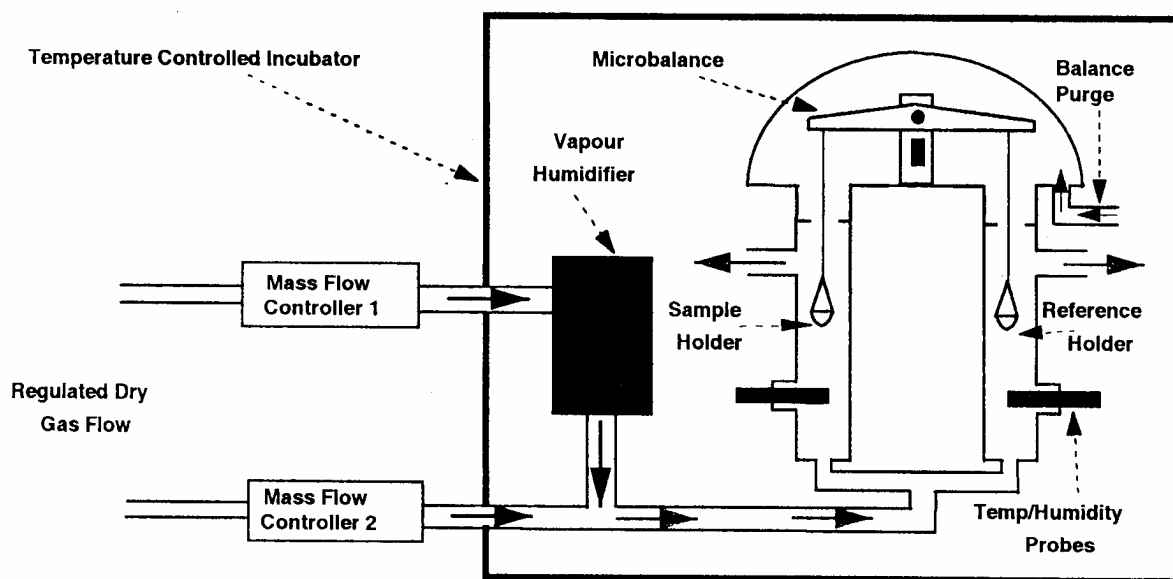

Figure 1: Schematics of the equipment used in drying experiments (DVS)

Table 1: Drying conditions used in experiments

Y (g water/kg dry air)	RH (%)		
	30ºC	40ºC	50ºC
0	0	0	0
10.65	40	23.0	13.8
16.11	60	34.5	20.7
21.67	80	46.0	27.5
27.32	100[a]	57.5	34.4

[a]reference value

RESULTS AND DISCUSSION

The selected samples of banana has initial moisture content 3.33 ± 0.07 (g/g, dry basis), which is equivalent to 76.8 ± 0.4 % in wet basis. The average initial value of the apparent density was 0.984 ± 0.004 g/cm^3. The average dry sample true density was 1.437± 0.001 g/cm^3.

Surface Area

The values of area available for heat and mass exchange were calculated from the experimental data presented by Katekawa and Silva (2004). Material is considered to keep its cylindrical shape during the drying and, therefore, transfer area can be calculated by a geometric expression.

For the calculation of the drying fluxes, the data presented in Figure 2 were fitted by a straight line, presented in Equation 1. The results of the model fit are presented in Table 2.

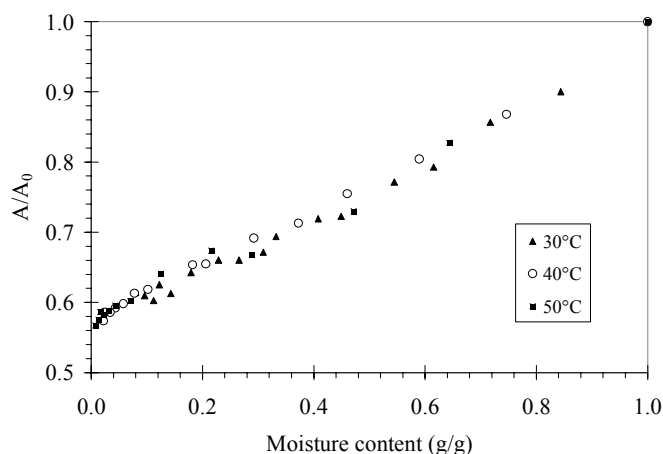$$\frac{A}{A_0} = a \frac{X}{X_0} + b \qquad (1)$$

The behavior of the transfer area is linear in almost the entire moisture content range, for the three temperatures. A deviation from linearity at low values of moisture content can be observed, mainly for the experiment at 50 °C. In the moisture content range where data from all experiments overlap, the variation of the transfer area was not significantly influenced by drying temperature.

Figure 2: Variation of exchange surface area as a function of moisture content

Table 2: Fit results

	30°C	40°C	50°C
a	0.41 ± 0.01	0.41 ± 0.01	0.41 ± 0.01
b	0.57 ± 0.01	0.56 ± 0.01	0.572 ± 0.006
R^2	0.98	0.99	0.99

Drying Periods

The experimental results of drying at 40ºC are presented in the Figure 3. The behavior of drying in relation to the value of relative humidity is as expected – the higher the value of relative humidity, the slower the process. In Figure 4, the values of drying rates calculated numerically from the data of Figure 3 are presented. Note the positive influence of the reduction of the relative humidity on the drying rate. Furthermore, despite the values of drying rate being modified, the value of the critical moisture content practically remains constant for the same temperature. Critical moisture content observed in Figure 4 is around 0.6 g/g, or around 0.18 of reduced moisture content, which is similar to the 0.2 value found by Jannot et al., 2004.

Also noticeable is the non existence of a constant rate period, in all experimental conditions. As described previously, this is an effect of the reduction of the transfer area of the sample. This reduction of the available area of mass transfer leads to a reduction in the drying rate.

The determination of the drying flux eliminates this effect of the variation of transfer area. The values of drying flux, calculated by the ratio between the values of drying rate from Figure 4 and the reduced area of the sample, in function of moisture content, is presented in Figure 5.

The observations of the classic theory of drying periods can be made considering Figure 5. During the first period of drying, the drying flux, or rate for unit area, is function only of the external conditions (relative humidity in Figure 5). In the second falling rate period, the flux is equal for all conditions.

The reduction in the transfer area, and the consequent effect on the drying rate, only occurs if mass transfer and shrinkage occur in orthogonal directions. As in the experiments the shrinkage was significant in both axial and radial directions, the reduction of exchange area was inevitable.

The observations made for the experiments at 40ºC also apply to those at 30 and 50ºC, for the drying curves, rates and fluxes.
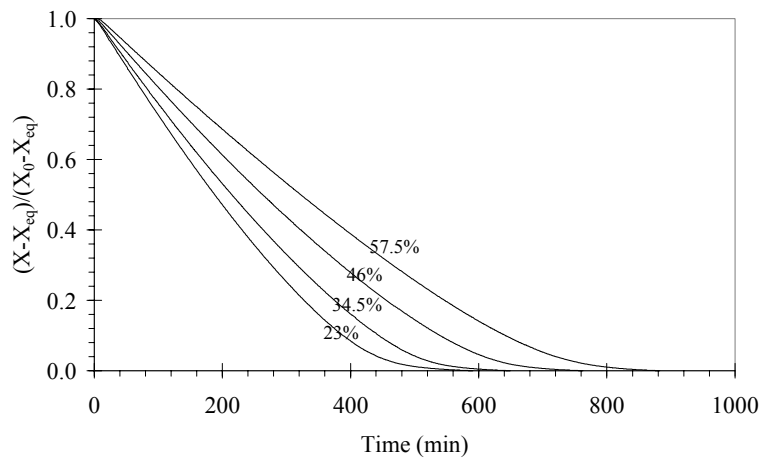
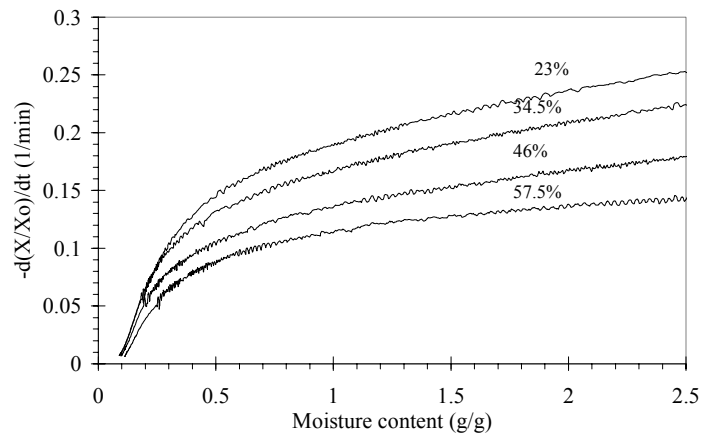**Figure 3:** Drying Curves (40ºC) – experimental data
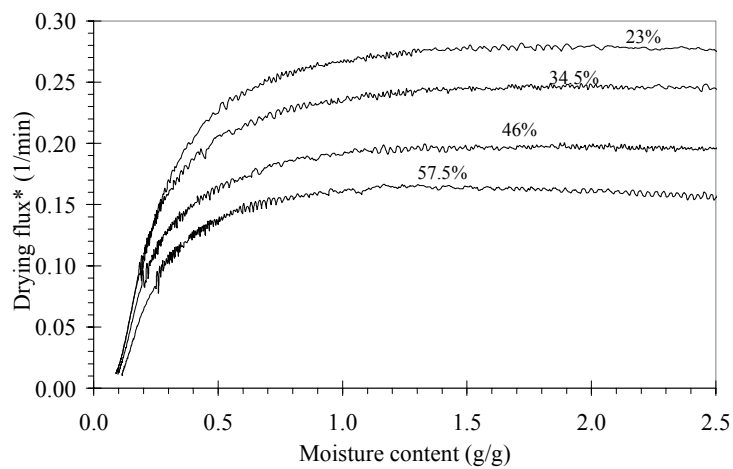

Figure 4: Drying rates (40ºC)

Figure 5: Fluxes normalized by exchange area calculated from Eq. 1 (40ºC)

Final Moisture Content

Figure 6 presents the graph of the final sample moisture content as a function of the relative humidity and temperatures values used in the experiments. As the equilibrium moisture content was reached at the end of each experiment, this figure represents, essentially, the equilibrium moisture contents at the selected relative humidity values for the three temperatures used. It must be stated that these values were obtained from samples of different fruits. These values are important to determine the end point of a drying process and to define the storage conditions.
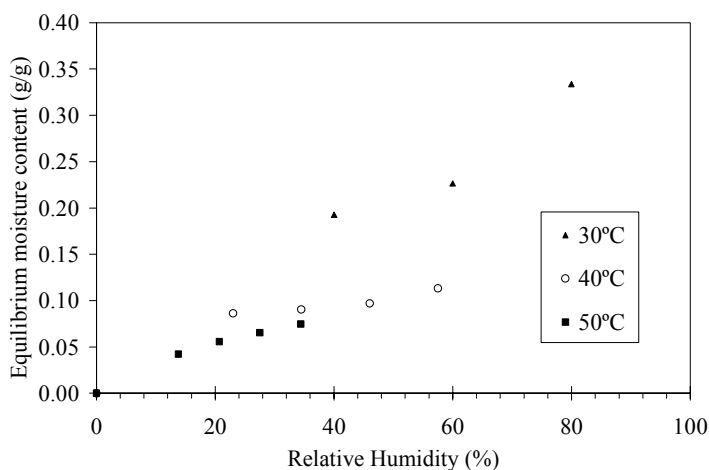

Figure 6: Final (equilibrium) moisture content as a function of relative humidity and temperature

Final Volume

Figure 7 presents the final reduced sample volume as a function of the relative humidity and temperatures values used in the drying experiments. The value of the final volume of each sample was measured after the sample reached equilibrium with the respective drying atmosphere.

Relative humidity does not have significant influence on the final volume for samples dried at 30 and 40ºC. For the drying the 50 ºC, apparently, lower sample volumes are obtained at lower values of relative humidity. Krokida and Maroulis (1997) obtaqined even greater extents of shrinkage for banana samples dried at 70ºC.

In the experiments at 50ºC, the difference in final volumes is probably due to the different final moisture contents, as it can be observed from Figures 6 and 7. In the experiments at 40ºC, the final volume is not influenced by the relative humidity of drying because the values of final moisture content were close (see Figure 6).
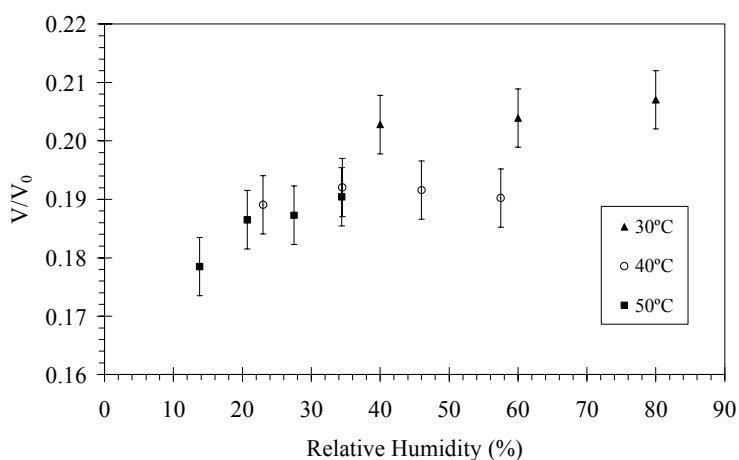

Figure 7: Final reduced volume as a function of relative humidity and temperature

Moreover, the final volume of the sample possesses a relation with the temperature of drying. At 40 and 50ºC the sample volumes underwent greater reduction drying than at 30ºC.

This last result may be explained by the theory of glass transition. Bodhrioua et al. (2002) reported a glass transition temperature for dried Cavendish sp. bananas of approximately 40ºC. Thus, the samples dried above this temperature become malleable at low moisture contents and undergo unrestricted shrinking. Samples dried below this temperature become rigid as moisture content approaches to zero and, therefore, have its volume reduction of volume restricted.

This way, at 30 ºC, the material would suffer to glass transition for all the conditions and, therefore, it presents lower volume reduction. At 40 ºC, the transition probably occurs at a later instant, in a way that the material shrinks more before becoming glassy. At 50 ºC, the material does not undergo transition and shrinks during the entire process.

These results are contrary to those presented in a previous work (Katekawa and Silva, 2004). In that work, the experimental conditions of drying were such that the drying rates were higher and the effect of case hardening was dominant.

Proof that different shrinking behavior at 50ºC in relation experiments at 30 and 40ºC can be achieved considering the glass transition temperature theory. For this analysis, the reader is referred to Katekawa and Silva (2007).

Drying Rate Equivalence

Figure 8 presents drying curves from selected experimental conditions. The proximity between the drying curves for the conditions of 30ºC and 40% RH and 40ºC and 57.5% RH is evident. This means that, starting from a reference state of 30ºC and 100% RH, the reduction of the relative humidity down to 40% has similar effect on drying kinetics

than the heating up to 40ºC and consequent reduction of the relative humidity to 57.5%.

Likewise, starting from a hypothetical atmospheric condition of 30ºC and 60%, heating up to 40ºC promotes reduction of the relative humidity 34.5%, as seen in Table 1. Heating the drying agent has a positive effect on the drying kinetics. However, it is observed in Figure 8 that this positive effect is similar to the reduction of the relative humidity from 60 to 0%, with no heating. To reach equilibrium moisture content at 40ºC and 34.5% (X = 0,095 g/g), the necessary time is 650 minutes. The same value of moisture content is reached after 690 minutes at 30ºC and 0%.

These equivalences are valid while the samples are relatively wet, above the critical moisture content. After the transition from the first to the second drying period, the values of the drying rates decrease more quickly at lower temperatures, since the equilibrium moisture content values are higher.

As it can be seen in Figure 9, the transition from the first to the second drying period occurs at higher moisture contents for experiments at lower temperatures. Even when the drying rate values are close, as in the case of the experiments 40 ºC/57.5% RH and 30 ºC/40% RH, the values of the critical moisture content are different. As the value of equilibrium moisture content is also different in this case, it can be said that the drying process occurs in similar way dislocated in the moisture content axis (in Figure 9).

There is no possible drying rate equivalence between experiments at 50 and 30ºC. Starting from any atmospheric condition at 30ºC, the highest possible value of relative humidity at 50ºC is 34.4%. The drying process is significantly faster in this condition than at 30ºC and 0%, as shown in Figure 10.

Likewise, in experimental conditions used in this work, there is no equivalence between conditions at 40 and 50ºC. The most drastic condition used at 40 ºC leads to a drying process slower than the blandest condition at 50 ºC.
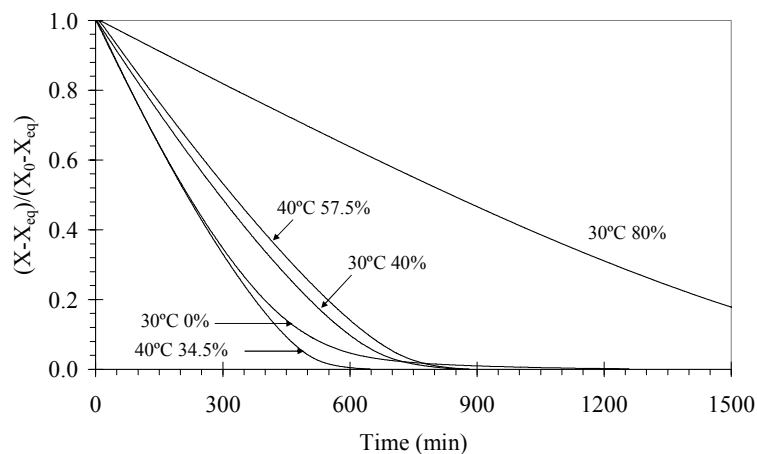

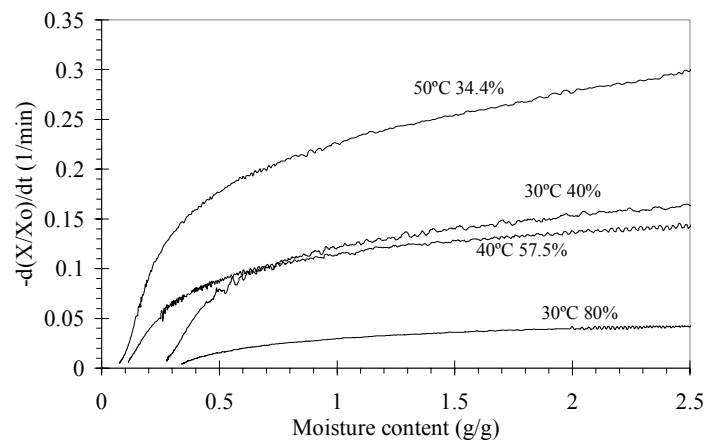**Figure 8:** Drying curves for selected experimental conditions at 30 and 40 ºC

Figure 9: Drying rates for selected experimental conditions at 30 and 40 °C
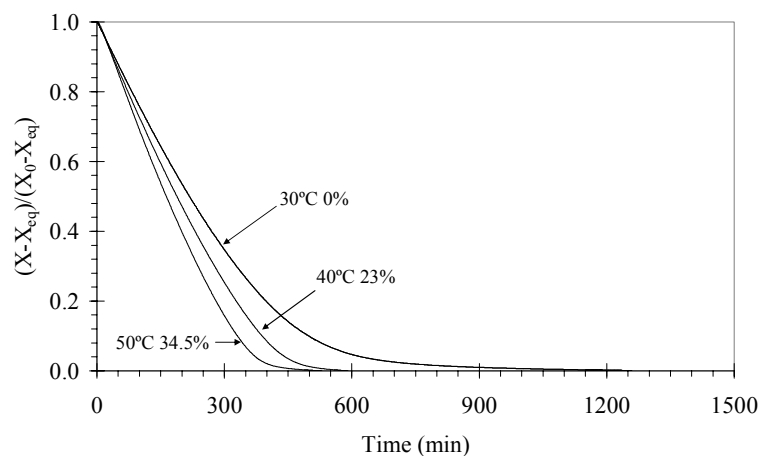

Figure 10: Drying curves for selected experimental conditions

CONCLUSIONS

The existence of a constant drying flux period was observed only when the variation of the exchange area is taken into account, which is evidence that the shrinkage is two-dimensional for the samples used. Relative humidity influenced only the drying rate values, but the overall shape of the drying rate curve was not modified. Temperature had influence both in the values and in the shape of the drying rate curve.

Relative humidity, though determinant in the values of drying rate, did not present significant influence on the volume reduction of the dry sample. On the other hand, the influence of drying temperature was pronounced and was explained by the glass transition theory.

Experimental observations were contradictory to those obtained in a previous work, where similar drying atmospheres were used, though the fluid dynamics of the drying gas were different. This contradiction evidences that the isolated parameters of temperature, relative humidity and, possibly, velocity of the drying gas are not enough to predict the behavior of the samples during drying. The compilation of these parameters into the values of drying rate and moisture content gradients is more adequate for description of the characteristics of the shrinkage process during drying.

For the experimental conditions used, the effect of temperature on the drying rate was more significant of that of the relative humidity. With this, the drying was faster in the worse condition of relative humidity at 50 °C than in the most propitious conditions at 40 and 30°C.

Among the drying experiments at 40 and 30°C, it was possible to establish some drying rate equivalences, so that similar drying kinetics is obtainable through either heating or relative humidity reduction of the drying agent.

In the studied case, the selection of the appropriate drying conditions is not only the

question of the energy costs of heating or drying of the gas. Aside from lower moisture contents and faster process times, drying at temperatures above glass transition temperature lead to lower sample volumes.

ACKNOWLEDGEMENTS

NOMENCLATURE

A	Exchange area	m^2
a, b	Coefficients from Equation (1)	(-)
RH	Relative humidity of the drying agent	%
t	time	min
V	Volume	m^3
X	Moisture content, dry basis	(g water)/ (g dry solid)
Y	Absolute humidity of the drying agent	(gwater)/ (kg dry air)

Subscripts

eq	Equilibrium value	(-)
0	Initial value	(-)

REFERENCES

Boudhrioua, N., Michon, C., Cuvelier, G and Bonazzi, C., Influence of ripeness and air temperature in banana texture during drying. Cavendish and Gros Michel banana slices, Journal of Food Engineering, 55, 115 (2002).

Demirel, D. and Turhan, M., Air-drying behavior of Dwarf Cavendish and Gros Michel banana slices, Journal of Food Engineering, 59, 1 (2003).

IEA. Banco de Dados IEA. Available at: www.iea.sp.gov.br/. Accessed on: May 11th, 2007.

Jannot, Y.; Talla, A.; Nganhou, J. and Puiggali, J.R. Modeling of Banana Convective Drying by the Drying Characteristic Curve (DCC) Method. Drying Technology 22, 1949 (2004).

Katekawa, M.E. and Silva, M.A., Study of porosity behaviour in convective drying of bananas, Proceedings of the 14th International Drying Symposium, vol. B, 1427, Sao Paulo (2004).

Katekawa, M.E. and Silva, M.A, On the influence of glass transition on shrinkage in convective drying of fruits: a case study of banana drying, Drying Technology, 25, No. 10, 1659 (2007).

Krokida, M.K. and Maroulis, Z.B. Effect of drying method on shrinkage and porosity. Drying Technology 15, 2441 (1997).

Lozano, J.E., Rotstein, E. and Urbicain, M.J., Total porosity and open-pore porosity in the drying of fruits, Journal of Food Science, 45, 1403 (1980).

Mayor, L. and Sereno, A.M. Modelling shrinkage during convective drying of food materials: a review, Journal of Food Engineering, 61, No. 3, 373 (2004).

MAPA - Ministério da Agricultura, Pecuária e Abastecimento. Agricultura brasileira em números – Anuário 2005. Available at: www.agricultura.gov.br. Accessed on May 11h, 2007.

Moropoulou, A.; Karoglou, M.; Giakoumaki, A.; Krokida, M.K.; Maroulis, Z.B. and Saravacos, G.D. Drying kinetics of some building materials. Brazilian Journal of Chemical Engineering 22, No. 2, 203 (2005).

Nogueira, R. I. and Park, K. J., Drying parameters to obtain "banana-passa", Drying '92, A, 874 (1992).

Perré, P.; May, B.K., The importance of considering exchange surface area reduction to exhibit a constant drying flux period in foodstuffs, Journal of Food Engineering, 54, 271 (2002).

Queiroz, M.R. Estudo teórico-experimental da cinética de secagem de bananas, PhD Thesis, Universidade Estadual de Campinas, (1994). In Portuguese.

Rahman, M.S. Toward prediction of porosity in foods during drying: a brief review, Drying Technology, 19, No. 1, 1 (2001).

Ratti, C. Shrinkage during drying of foodstuffs, Journal of Food Engineering, 23, 91 (1994).

Talla, A.; Puiggali, J.R.; Jomaa, W. and Jannot, Y. Shrinkage and density evolution during drying of tropical fruits: application to banana. Journal of Food Engineering 64, 103 (2004).

Waje, S.S.; Meshram, M.W.; Chaudhary, V.; Pandey, R.; Mahanawar, P.A. and Thorat, B.N. Drying and shrinkage of polymer gels. Brazilian Journal of Chemical Engineering 22, No. 2, 209 (2005).