ESTIMATION OF THE THERMAL DIFFUSIVITY IN SOY GRAINS AT FUNCTION OF GRAINS MOISTURE CONTENT

Pedro Augusto Pereira Borges
UNIJUI, DeFEM – Rua São Francisco, 501 – Ijuí, RS
pborges@unijui.tche.br

Jean Lucas da Silva
UNIJUI, DeFEM – Rua São Francisco, 501 – Ijuí, RS
jean_mmm@hotmail.com

Angeli Cervi
UNIJUI, DeFEM – Rua São Francisco, 501 – Ijuí, RS
agelicervi@detec.unijui.tche.br

Abstract. *The soy grain is composed by organic matter disposed in different ways at each point. Rinds, moisture matter, canals, pores and water all form a complex with different thermal diffusivity. The mathematical modeling detailed of each point becomes very difficult because of the geometrical complexity and the identification needed for each part. The objective of this work is to develop a method to estimate the thermal diffusivity in soy grains as an uniformed way, for the different moisture content of the grain. Heating grain experiments were done in a oven, with an air temperature between 60 e 130, with different moisture content of the grain, between 0,10 e 0,27 b.u. To estimate the thermal diffusivity an analytical solution of the energy equation in the spherical coordinates system was used, with boundary conditions of the first kind and solved the inverse problem with base on experimental data of the heating of the grains. A mathematical diffusive model of heat transference was proposed with variable thermal diffusivity in function of the moisture content.*

Keywords*: Thermal diffusivity, drying grain, numerical methods*

1. Introduction

The soy grain is a composition of organic matter disposed in different ways at each point. Rinds, humid matter, canals, pores and water form a set that behaves thermally different during the drying grain process (Brooker, 1974). The detailed mathematical modeling of each point becomes very difficult because of the geometrical complexity and the identification needed of the thermal characteristics of each part. The determination of the thermal diffusivity of the grain it is useful because this parameter is used in mathematical models of drying (Khatchatourian *et al* .,2001), currently very used for monitoring and project the industrial dryiers.

The grains heat transfer coefficients found in literature refers to the product of other countries like in Loncin(1979), Miketinac et al. (1992) e Oliveira e Haguigui (1998) or present data about band temperatures, under those used in modern dryers. In Oliveira e Haguigui (1998) the heat and mass transfer coefficients were considered constant in a drying multi- particle model. In Krokida et al (2002) were selected some data in literature about the heat and mass transfer coefficients. In Borges et al (2004) was showed that using a thermal diffusivity variable it is possible to describe the variations in temperature of the grain with better precision. The present work has as an objective to add to the influenced of the moisture content of the grain in the thermal diffusivity. With base of experimental data of heating grains in different moisture contents (*0,10* e *0,27* w.b.- wet basis), the thermal diffusivity was estimated through the inverse problem method, and expressed like a parameter that depends on the moisture content.

2. Experiment Description

Were carried through experiments of the heating of grains with different moisture content, for the estimation of the thermal diffusivity. Samples of *10* grains were moistured with distilled water, until it reached a moisture content superior to *0,24 w.b.* . The samples were heated with oven temperature of *273 K* with different time intervals, so that each sample had a different moisture content, right after placed in repose (at least *24h*) to homogenize the distribution of the moisture. The moisture content was measured using a gravimetric method (Brooker, 1974). Half of each sample was separated to calculate the initial moisture content. The other half was reserved for the determination of the heating curves. The heating of the grains was done in a oven, with constant temperature, of *10* in *10 K*, at a interval of *333* to *403 K*. The temperature was measured using small thermocouples introduced at the center of the grains and connected to a data acquisition system as show the Figure 1. Each curve of heating was obtained by the average of the measurements of the temperature, performed in five grains, these all placed together in the oven.

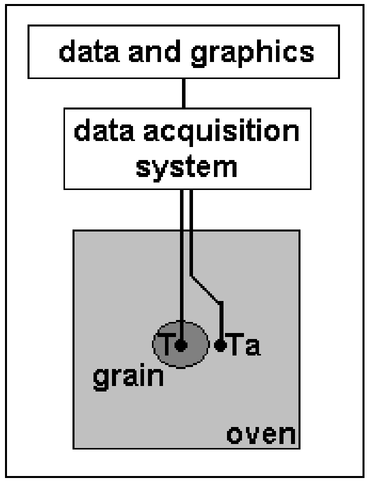

Figure 1: General project of the experiments of heating of the grains in the oven. T e T_a indicates the positions of the thermocouples, where the measurement of temperature of the interior of the grains and the air of the oven were done, respectively.

The Figure 1 shows the experimental data of the grains heating curves for each temperature. The grains temperature are not perfectly assimptotics to the horizontal lines of the respective temperature indicated, for two reasons: first, the temperatures were obtained through measures and secondly because the correction of the reading of the thermocouples (result of the calibration) was done posterior to the obtained of the experimental data.

3. The direct problem

To estimate the thermal diffusivity (α) using the numerical method was necessary to solve before the direct problem of heat transference in the soy grain. These grains have an ellipsoid shape, however with different small differences between the diameters, for that, in this work the shape of the grains will be considered spherical.

The heat transference problem in the spherical soy grain, with initial temperature T in all points, immersed in a oven with constant temperature T, was modeled through the known equation of energy in spherical coordinates.

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(kr^2\frac{\partial T}{\partial r}\right)+\frac{1}{r^2\, sen\theta}\frac{\partial}{\partial\theta}\left(k\, sen\theta\frac{\partial T}{\partial\theta}\right)+\frac{1}{r^2\, sen^2\,\theta}\frac{\partial}{\partial\phi}\left(k\frac{\partial T}{\partial\phi}\right)+g=\rho C_p\frac{\partial T}{\partial t} \quad (1)$$

where T is the grain temperature (K),
k is the grain thermal conductivity ($Wm^{-1}K^{-1}$),
g is the heat source (Js^{-1}),
ρ is the grain specific mass ($kg\ s^{-1}$),
C_p is the grain specific heat in constant pressure ($J\ kg^{-1}K^{-1}$),
θ, ϕ e r are the spatial variables in spherical coordinates (m),
t is the time (s).

The derivatives $\partial T/\partial\theta$ *and* $\partial T/\partial\phi$ are null for a constant temperature, in relation the variables θ and ϕ. Because there is no heat source the interior of the grain, g it is also null. So, considering constant α constant for small time intervals, the equation (1) becomes

$$\frac{\partial T}{\partial t}=\alpha\left[\frac{2}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial r^2}\right] \qquad \text{in } 0<r<R \quad \text{for} \quad t>0 \quad (2)$$

where α is the thermal diffusivity (m^2s^{-1}), defined as $\alpha=\dfrac{k}{\rho C_p}$. (3)

The boundary conditions for the heating with the air temperature *Ta* constant and without the air movement (heating in oven) are the first kind can be written as

$T(R,t) = T_a$ for $t > 0$ (4)
$T(r,0) = T_o$ in $0 \leq r < R$ (5)

where R is the grain radius.

The solution of the equation (2) with boundary conditions (4) e (5) was obtained through the variables separation method, in the form of a Fourier series.

$$T(r,t) = \frac{1}{r}\left[rT_a + \frac{2R}{\pi}(T_a - T_o)\sum_{n=1}^{\infty}\frac{(-1)^n}{n}\, sen\left(\frac{n\pi r}{R}\right).e^{-\alpha\left(\frac{n\pi}{R}\right)^2 t}\right] \qquad (6)$$

4. The inverse problem

The diffusivity was calculated with basis on experimental data - considering the grain in its spherical shape and the thermocouple placed at the center of the grain- through the resolution of the inverse problem, using the solution of the direct problem given by the equation (2). A computational program was developed following the given steps:

1) Entrance of the experimental data: $T_{exp}(t)$
2) Definition of the error ε admitted at the *T* calculation.
3) Initial estimation of thermal diffusivity α.
4) Solving the direct problem whit estimated α . To obtain $T(t,\alpha)$.
5) Calculation of $J = T(t, \alpha) - T_{exp}(t)$.
6) If $|J| < \varepsilon$ than go to 9^o step.
7) If $J < 0$ than $\alpha = \alpha + \alpha/m$.
   If $J > 0$ than $\alpha = \alpha - \alpha/m$.
8) Returns to step 4.
9) The estimate value of diffusivity is α.

where J is the difference between the calculated and experimental temperatures and
m is the fraction of α convenient to add or diminish at each interaction.

5. Relationship between grain thermal diffusivity and moisture content

The analyze of the values distribution of the diffusivity in function of the moisture content showed that this would not have significantly for different air temperatures of the oven (T*a)* and showed a distribution with linear tendency in relation to the moisture content. The results of the inverse problem are showed in Figure 2. Making curves adjustment about theses data considering the linear function,

$$\alpha(M) = dM + b \qquad (7)$$

were obtained $d = -1.0498\ 10^{-7}$ e $b = 9.0019^{-8}$ as parameters of adjustment.

6. Result Discussion

The results obtained using the inverse problem might contain imprecision because of the hypothesis adopted. For example, the spherical shape of the grain, the exact position of the thermocouples and the precision of the temperature measurements: the soy grains, when moistened have an ellipsoid shape, having a spherical shape, as they dry; it is very difficult to make sure if the thermocouple sensor is exactly at the center of the grain, or a little dislocated, and the temperature measurement might contain minor systematic errors or calibration errors, even with all the effort made to minimize them. This considerations justify the use of the term ``estimation``, rather than ``determination`` of the diffusivity. Eventhough, the results obtained are at the same superior order as the verified data in the literature, for example, in Brooker *et al.*, 1974.

On the grain heating curves, showed in Figure 4, it is observed that the time for the grain temperature (*T*) reaches the oven temperature (*Ta*) is inferior to *450 s*. Calculating the thermal diffusivity in function of time was observed that it tends to zero as time tends to the infinitive. This make impossible the direct calculus of the thermal diffusivity in function of time or even of the grain temperature. Through Fourier´s law, the heat flow is proportional to the gradient temperature. Where the proportional constantly is the thermal conductivity. As time increases, the heat tends to zero, not because the conductivity (or diffusivity) tends to zero, but because the gradient tends to zero, because *T* tends to *Ta*. So, the grain diffusivity doesn't become null when *Tg* = *Ta* as the results of the inverse problem suggest. What does become null, in this case, is the heat flow. For this motive, in this work, the inverse problem was applied only in the first *10* minutes of the grains samples heating with different moisture contents, to calculate the diffusivity. This procedure was done to obtain the diffusivity value that represents the grain initial state moisture, since at his time interval the moisture variation is very small, as showed in Figure 3.

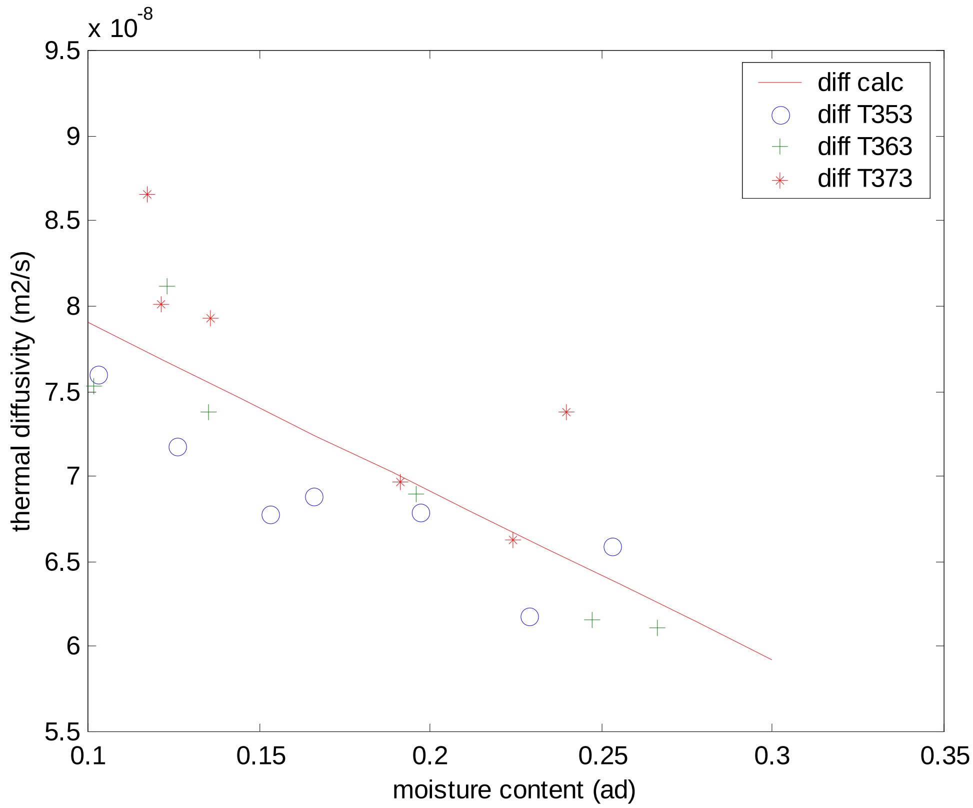

Figure 2 - Thermal diffusivity variation with moisture content –results of the inverse problem.

The diffusivity is a grain thermal property that depends only of internal factors of the grain: chemical constitution, physical arrangement of the canals, layers, specific mass… and temperature. The heat amount in the grain interferers the size of the canal and with this, on the water movement. On the other side, the loss of water generates modifications on the grain structure, altering the specific mass, the thermal conductivity and, as a consequence, the thermal diffusivity.

Figure 2 represents the variation of the thermal diffusivity (α) in relation to he moisture content (*M*). In the heating process (drying) the grains mass changes, decreasing the thermal effects of water and becomes prevalent the heat transference through conduction by the mass of the grain. The data in Figure 2 show that the thermal diffusivity decreases as the moisture content increases. So then, as the grain dries, the diffusivity increases in the grains. This fact is comprehensible considering that the mass diffusivity is larger than the water diffusivity **(**Brooker *et al.* , 1974). The influence of the moisture content on the thermal diffusivity is of the order of *20%*.

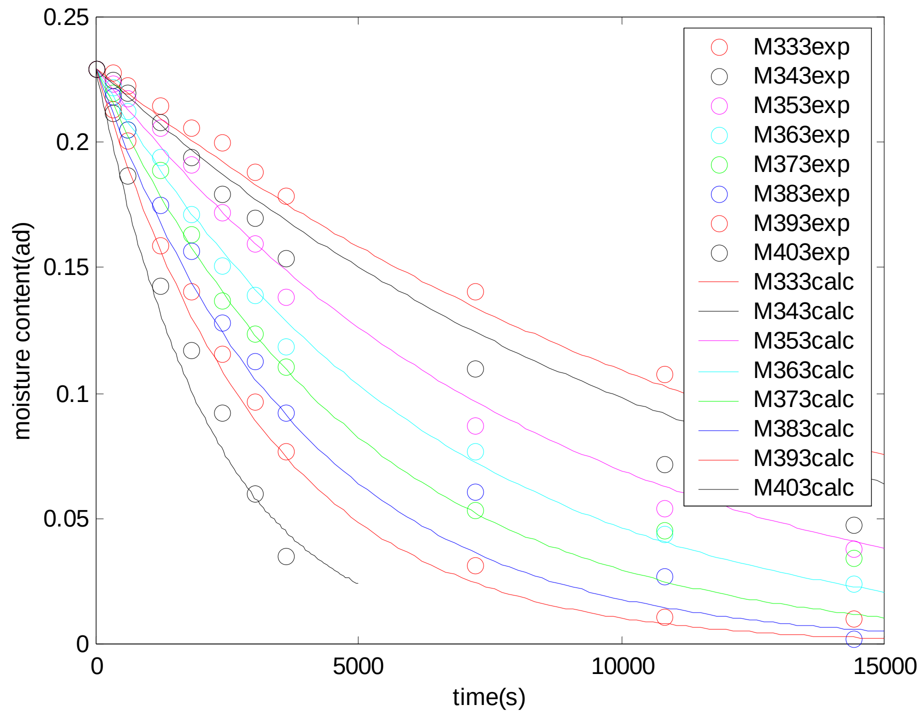

Figure 3 – Variation of the moisture content of the grain on the drying dimensional process.

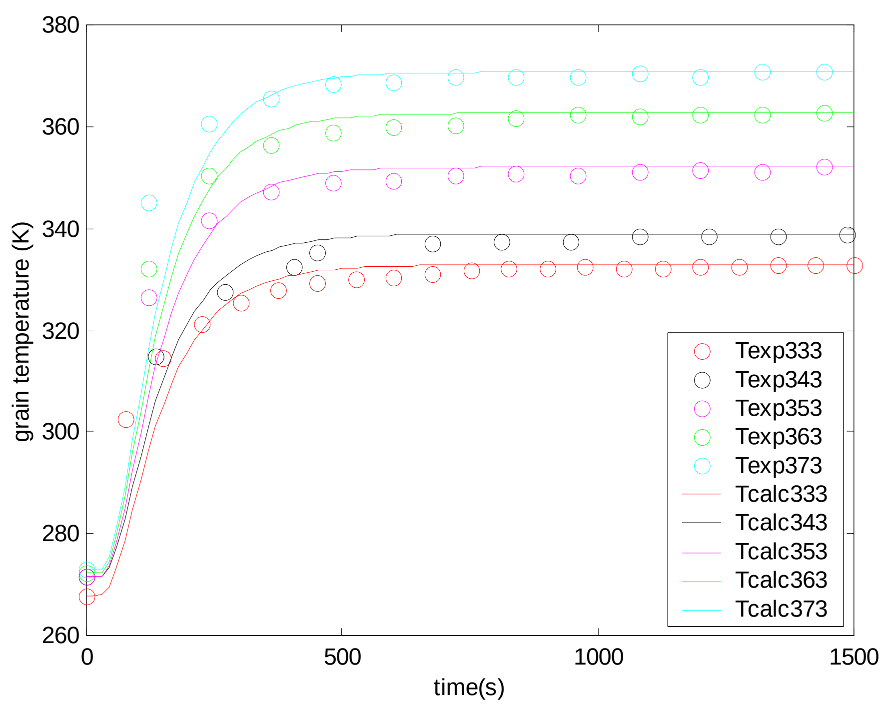

Figure 4 – Comparison between the experimental data and calculations through the model with variable diffusivity, for different drying temperatures.

To consider the constant thermal diffusivity for small periods of drying don't constitute of big error on the calculation of the grain temperature, because the variation of the moisture content (see Figure 3), is the consequent variation of diffusivity (see Figure2), are not significant. However, for the calculation of the grain temperature in drying models, is important to consider the initial moisture content with it define the diffusivity. The diffusivity influence on the calculus of the grain temperature can be observed in Figure 5, which shows the temperature curves calculated with different values of diffusivity, obtained in the moisture content interval, studied in this work.

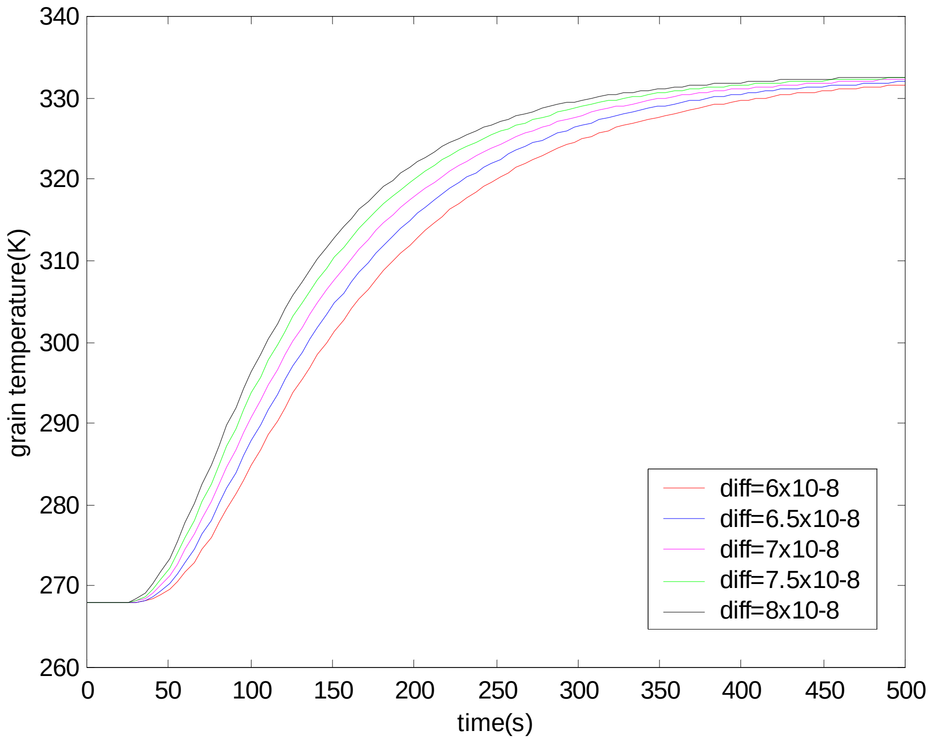

Figure 5 – Influences of the thermal diffusivity variation on the grain temperature, with the moisture content varying between *0,10* and *0,27*.

7. Conclusions

Heating experiments of soy grain were realized with different moisture contents and established a linear relationship between the thermal diffusivity and the moisture content. This relationship showed itself to be inversely proportional (as the moisture content increases the diffusivity decreases.) and varies 20% at the moisture content interval between *0,1* to *0,27 w.b.*.

It was showed that the influence variation of the moisture content, and the consequent modification of the thermal difusivity on the calculus of the grain temperature, is not significant for the time intervals in which the grains are capable of drying in industrial dryers (less than *20* minutes). In this case, the diffusivity can be considered constant. However, for the calculus of the grain temperature in drying models, which modeled general situations (drying grains with high moisture content), it is necessary to define thermal diffusivity considering the variation of the moisture content of the grains.

Considering the knowledge importance of the parameters of heat exchange for the mathematical modeling of the drying process and the diversity of the grains produced in Brazil, this work has sequences on the development of technique to the research of thermal diffusivity of other grains (barley, oat, corn, …) in which its base is the current work.

8. Acknowledgements

We thank the CNPq for the scholarships for masters degree and Scientific Initiation and UNIJUI for the institutional data support for the realization of this work.

9. References

Borges, P.A.P.; Oliveira, J.F.S. e Klamt, V. , 2004. Estimação do coeficiente de transferência de calor por convecção de grãos de soja. In Proceedings of XXV Iberian Latin American Congress in Computational Methods in Ingineering - XXV CILAMCE,. Recife. CD-ROM.

Brooker, D.B., Bakker-Arkema and Hall, C.W., 1974. *Drying cereal grains*, Westport, Connecticut, The Avi Publishinhg Company.

Khatchatourian, O.A., Borges, P.A.P. and Petry, V.J., 2001. Mathematical model and numerical methods for simulation of dynamics of drying of soy grains in camera of fixed bed**,** In: Proceedings of LACAFLUM 2001 - *V Latin American and Caribbean Congress on Fluid Mechanics*, DHT-4, pp1-6, Universidad Simón Bolívar, May 14 – 17, Caracas, Venezuela.

Krokida, M.K., Maroulis, Z.B. and Marinos-Kouris, D., 2002. Heat and Mass transfer-coefficients in drying: compilation of literature data. *Drying Technology*, 20(1), 1-18.

Loncin, M. and Merson, R.L. 1979. In: *Food Engineering: principles and selected applications*, Academic Press, New York, USA.

Miketinac, M. J., Sokhansanj, S. and Tutek, Z. 1992, Determination of Heat and Mass Transfer Coefficients in thin Layer Drying of Grain. *ASAE*, vol 35(6): Nov-Dec, p.1853-1858.

Oliveira, L.S. & Haguigui, K., 1998. Conjugate heat and mass transfer in convective drying of multiparticle systems: Part I: Theorethical Considerations, *Drying Technology*, v. 16, Issue 3-5, p.433-461.

10. Responsibility notice

The authors are the only responsible for the printed material included in this paper.