Heat and mass transfer analysis of convective drying of chickpea (*Cicer arietinum*)

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Abstract. The objective of this article is to describe the modelling and simulation of the dehydration of chickpea in a complex drying system process, using COMSOL Multiphysics Program. A model, based on mass and energy balances, was developed for the simulation of unsteady convective drying with air (3.0 m/s and 60 °C). The program predicted an 8 hours-dehydration time, with an effective moisture diffusivity of $3.1 *10^{-10}$, which was experimentally obtained. The empirical model that best represented the process was the exponential one.

1. Introduction

Chickpeas, (*Cicer arietinum*), also known as *garbanzos* are grown in plants between 20-50 cm high that have small leaves on either side of their stems. Chickpeas are a type of pulse, with one seedpod containing two or three peas. There are two main kinds of chickpeas: *Desi*, cultivated mostly in the Indian subcontinent, Ethiopia, Iran, and Mexico; and *Kabuli*, which has lighter colored, larger seeds and a smoother coat, mainly grown in Southern Europe, Northern Africa, Pakistan, Afghanistan, India and Chile. In 2011, 132 000 tons were produced in Mexico for human consumption in approximately 90 000 cultured ha [9].

Drying has a negative environmental impact because the thermal energy that it requires is obtained from the combustion of fossil fuels. It has been estimated that from 10 to 25% of the national industrial energy consumption is applied to thermal dehydration in industrial countries [7]. As global economies succeed, the request for energy used in drying increase. Thus, there is need to know this operation and to guarantee that it is carried out as efficiently as possible within the economic limitations of the market. It is also important to keep abreast with the recent drying systems, as well as the emerging new ones.

Drying has been used from ancient times to preserve food products. Open-air drying is the most commonly used technique, especially in tropical and subtropical regions. However, several difficulties are usually confronted [7]: product destruction caused by some insects; product degradation due to direct exposure to sun light, rain, and morning dew; contamination with strange particles and smokes due to air pollution; potential cracking of the product and loss of germination capacity; decrease of quality during storage due to inefficient drying. Open air drying is also a common practice for chickpeas; in hot weather, it takes from 15 to 20 days to achieve complete drying of the grains. Thus, alternative drying methods, such as those based on solar energy may imply important savings and effective advantages, if these drying times can be cut off while the product quality is preserved.

Dehydration process involves the simultaneous transfer of mass, heat, and momentum in which the moisture is removed by evaporation into an unsaturated gas phase. Due to the complexity of the drying process, no generalized model exists to explain the mechanism of internal moisture movement. Although it is now recognized that in most practical conditions of air drying of products the principal rate determining step is internal mass transfer, there is no agreement on

the method of internal moisture movement [1]. In the case of porous materials such as fruits and vegetables, interstitial spaces, capillaries and gas filled cavities exist within the food medium and water transport takes place via several possible mechanisms acting in various arrangements. Most of fruits and vegetables are categorized as capillary porous media or capillary porous colloids, therefore, it is often suggested that a combination of capillary flow and vapor diffusion mechanisms should be used to describe internal moisture transfer [3].

The heat and mass transfers in the bodies are determined by the structure of the substance. The agricultural products are anisotropic, inhomogeneous and complex. In natural materials structural and dimension fluctuations happen during environmental changes or artificial external conditions. These variations result hysteretic type functions (e.g. sorption isotherms) [6]. These facts can also be basically true for inorganic materials, however in biological products phenomena appear together [3]. In order to get better acquainted with these methods we have to develop the mathematical simulations describing the heat and mass transfer processes from all physical correctly points of view. In the past authors basically dealt with the modeling of heat and mass transfer in cereal grains, and consequently have literature experiences first of all in this area [2, 4]. The simplifications were: (a) the grains were considered to be isotropic and homogenous, therefore moisture concentration gradient was used as the main driving force of the mass transfer; (b) all the transfer factors were considered to be constant; (c) complex models were primarily simplified to squared ones. As the result of these conditions the models could follow only in certain accuracy the integral moisture content changes or the average temperature changes. Experimental measurements are necessary as input factors for the simulations. For a better accurate model the knowledge of the forces potentials during heat and mass transfers is necessary. Water potential gradients as the driving force are used in contrast with the old practice (where moisture gradients were used) for modeling of mass transfer in chickpea.

2. Mathematical modeling of drying processes.

The basic governing differential equation system for the drying processes is given in [6], and simplified by Husain et al. [3] in the following form:

$$\frac{\partial X}{\partial \tau} = \nabla(D\nabla X) \qquad\qquad (1)$$

$$\rho\frac{\partial T}{\partial \tau} = \nabla k\nabla T + L\rho\frac{\partial X}{\partial \tau} \qquad\qquad (2)$$

where, X is the moisture content dry base; D is the diffusion coefficient; ρ is the density; T is the temperature; τ is the time; k is the thermal conductivity; L is the latent heat of vaporization of water. The previously mentioned simplifications were taken into account by other authors, who, for instance, analyzed the problem using different physical properties of the different constituents [2, 10]. Other way was to consider the coefficients as functions instead of constants [8]. The above equation systems proved that inner moisture distribution in e.g. a single chickpea, does not agree with the calculated distribution [4]. This equations system was solved with the COMSOL Multiphysics software.

The best numerical methods that describe the drying process result from the theories of irreversible thermodynamics in which the fluxes are taken to be directly proportional to the appropriate water potential gradients [1]. These considerations make possible to obtain the moisture contents and the temperature fields inside the grain solving the partial differential equations. These equations include transport coefficients which must be determined experimentally, and are functions of moisture content.

The physical composition characteristics are different for all food products; they depend on variety, location grown, climatic conditions, etc. The best sources of thermal property models are empirical rather than theoretical, they are prediction equations based on chemical composition, temperature and physical structure (density, porosity, size and configuration of void spaces), they are based on statistical curve fitting rather than theoretical derivations involving heat transfer analysis. The values of the physical variables used in the software such as the properties of the chickpea [7] are summarized in Table 1. Some values were taken from

the database that the program contains, and the diffusion coefficient value was obtained by experimentation

Table 1: Parameters used for the chickpea in the COMSOL Multiphysics software.

Nombre	Expresión	Valor	Descripción
T_air	60[degC]	333.15 K	Oven air temperature
T0	18[degC]	291.15 K	Initial patty temperature
rho_p	1383[kg/m^3]	1383.0 kg/m³	Density of patty
h_T	30[W/(m^2*K)]	30.000 W/(m²·K)	Heat transfer coefficient
c0	0.93*rho_p/M_H2O	71455 mol/m³	Initial moisture concentration
c_b	0.02*rho_p/M_H2O	1536.7 mol/m³	Air moisture concentration
C_m	0.003	0.0030000	Specific moisture capacity
k_m	1.29e-9[kg/(m*s)]	1.2900E-9 kg/(m·s)	Moisture conductivity
h_m	1.67e-6[kg/(m^2*s)]	1.6700E-6 kg/(m²...	Mass transfer coefficient in mass units
D	k_m/(rho_p*C_m)	3.1092E-10 m²/s	Diffusion coefficient
k_c	h_m/(rho_p*C_m)	4.0251E-7 m/s	Mass transfer coefficient
D_m	9.7e-9[m^2/s]	9.7000E-9 m²/s	Surface moisture diffusivity
lda	2.3e6[J/kg]*M_H2O	41400 J/mol	Molar latent heat of vaporization
M_H2O	18[g/mol]	0.018000 kg/mol	Water molecular weight

3. **Results and Discussion**.

COMSOL Mutiphysics program was used to simulate the dehydration of chickpea in a complex drying system processes, obtaining the numerical solution of the model equations. The above system of non-linear partial differential equations had been solved by the finite element method implemented by COMSOL Multiphysics 4.4, together with the already described set of initial and boundary conditions. We built the geometry of the model, and then were fixed the boundary settings, the mesh parameters and compute the final solution (Figure 1).

The chickpea has a height of 0.016 m and 0.019 m in diameter. The selected mesh was the triangular type and 6586 nodes or degrees of freedom were formed, for its fourth part, since it was considered symmetric, the air flow incided horizontally at a speed of 3.0 m/s and a temperature of 60 °C, as shown in Figure 2.
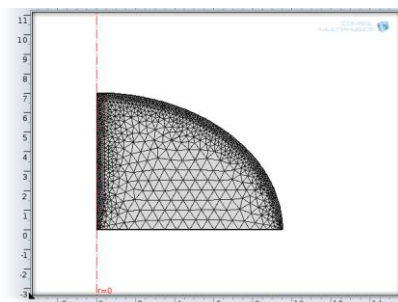

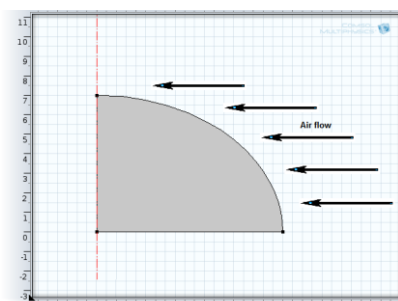**Fig. 1.** Mesh selected on the grain of chickpea.

Fig. 2. Incidence of air on the grain, the air speed and temperature were 3.0 m/s and 60 ° C, respectively.

The simulation with COMSOL program of hot-air drying began with an initial concentration in the sample of 67 000 mol/cm³ and the final was 5 000 mol/cm³, the used time was 8 hours, the obtained graph is displayed in Figure 3. This time is almost equal to that obtained experimentally and reported in [5], which was 8. 5 hours. At the beginning the moisture lost was

fast, in the first 30 minutes the mass decreased to 45% of its initial value, then the loss became slower. In the following 3.5 hours an additional 30% was lost and in the final stage, it took 4 hours to lose 7.5% of moisture content.
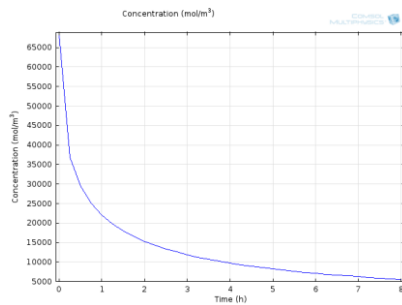

Fig. 3. Graph of the loss of concentration of mass against time.

These values were used to produce the corresponding moisture content vs time graph (Figure 4), to get the model of drying of the chickpea, which was logarithmic, the equation is:
$MR = 0.0397 + 0.5381exp(-1.4214\,t)$, with $R^2 = 0.934$, $\chi^2 = 0.00013$ and $RMSE = 0.00092$.

In the graph presented in Figure 5 the variation of the temperature against time in the center of the chickpea can be observed. It starts to gradually increase from 18 °C until it reaches the temperature of the drying air, 60 °C. The drying time was approximately 1 hour, and afterwards the temperature remained constant until the end of the simulation. This temperature was not experimentally obtained due to the technical difficulties involving the corresponding measurement.
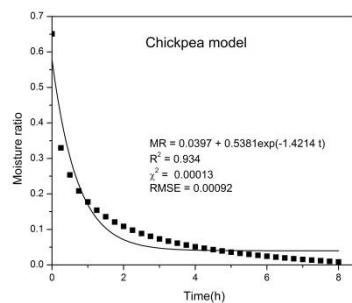

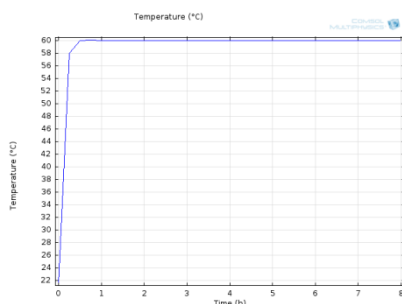**Fig. 4.** Logarithm model of chickpea drying.

Fig. 5. Temperature at the center of the sample of the chickpea.

In the sequence shown in Figure 6, drying process of the sample is displayed. At the start the whole grain has the same concentration of mass, as the simulation moves on the blue-color strip, which represents the lowest concentration, becomes wider, which indicates that the product is losing moisture. At the end of the drying time, it is observed that the concentration of mass in the center is quite small, 5 000 mol/cm^3. The color bar that appears on the right hand side corresponds to the values of concentration.
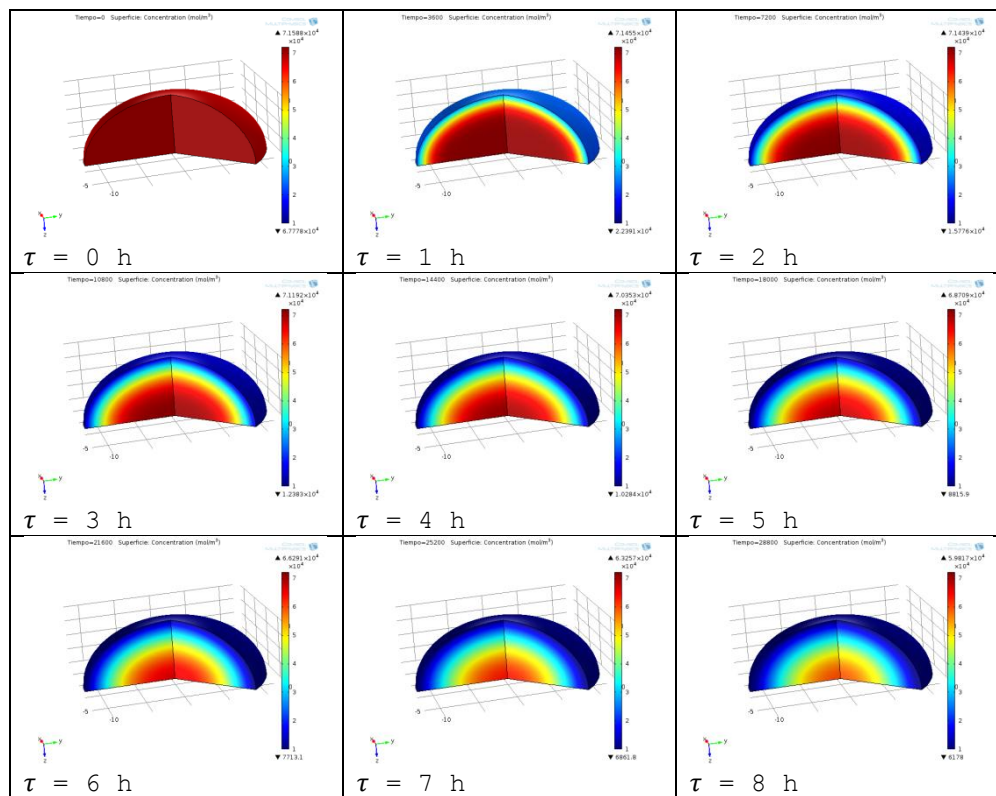
Fig. 6. Drying process of chickpea.

4. Conclusions.

The finite element method is applied to solve the heat and mass transfer equations of the drying of chickpea, regardig it as a composite biological material. The COMSOL Multiphysics software was used for the calculation of the model.

The process of drying a grain of chickpea has been simulated using air at a temperature of 60 ° C and 3.0 m/s speed. The initial temperature of the air was considered equal to the environmental one of 18 ° C. The initial concentration of mass in the sample was 67 000 mol/cm^3 and the final was 5 000 mol/cm^3, the time used in the simulation was 8 hours. This type of simulation allows the step-by-step observation of the phenomenon of drying. The drying temperature, 60 ° C, was reached in the center of the sample after an hour of the process start.

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