

Hydro-thermo-viscoelastic Based Finite Element Modeling of Apple Convective Drying Process

M. Toujani¹, R. Djebali², L. Hassini¹, S. Azzouz¹ and A. Belghith¹

Abstract: In the present work we aim to simulate unsteady two-dimensional evolution of the moisture content, temperature and mechanical stress in a parallelepiped apple sample during convective drying. The model is based on the heat and mass transfer equations and the mechanical equilibrium equation under the assumptions of plane deformation, viscoelasticity and isotropic hydric shrinkage. The Finite Elements COMSOL Multiphysics solver is used to solve the developed model. The hydro-thermal model was validated on experimental data drawn in our laboratory for moisture and temperature internal profiles of the product. Excellent agreement has been obtained between numerical and measured data for different drying temperatures. The hydro-thermal model was, then, implemented in a Finite Element hydro-thermo-viscoelastic developed model. Results for mechanical stresses are found to be in good agreement with former observations. It was found, also, that the maximum stress arises at the beginning of drying and holds at the top external surface of the sample which is the surface facing the airflow. The phenomenon is augmented by temperature.

Keywords: Convective drying, Finite Elements modeling, viscoelastic model, heat and mass transfer, deformation and mechanical stress.

Nomenclature

a_w	Water activity
C_p	Effective heat capacity (J/kg/K)
C_{pl}	Heat capacity of the liquid phase (J/kg/K)
D	Diffusion coefficient (m ² /s)
E	Young modulus (MPa)
$E(t)$	Relaxation function
E_i	Elastic modulus of branch i

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G	Shear modulus (MPa)
h	Heat transfer coefficient (W/m ² /K)
K	Bulk modulus (MPa)
k	Mass transfer coefficient (Kg/m ² /s)
L _v	Latent heat of water evaporation (J/kg)
Pr	Prandtl number
R	Universal gas constant (J/mol/K)
R _e	Reynolds number
RH	Relative humidity (%)
T	Temperature (°C, K)
t	Time (s)
u	Displacement (m)
v	Velocity (m/s)
X	Moisture content (Kg/Kg d.b.)
XR	Moisture ratio

Greek symbols

α	Linear shrinkage coefficient
β	Volume shrinkage coefficient
ε	Strain
λ	Thermal conductivity (W/m/K)
μ	Shear modulus (Pa)
ρ	Density (kg/m ³)
σ	Stress (Pa)
τ	Time of relaxation (= η / E)
η	Specific viscosity (MPa.s)
δ_{ij}	Kronecker's delta
ν	Poisson's ratio

Superscripts

x	x-direction
y	y-direction
m	mechanical

Subscripts

0	initial value
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<i>a</i>	air
<i>s</i>	solid
<i>l</i>	liquid
<i>t</i>	total
<i>h</i>	hydro

1 Introduction

Convection drying is one of the most frequently used processes for food dehydration. This technique requires high temperature and velocity of drying air, is very costly in processing time and final products are characterized by low porosity and high apparent density [Tsami, Krokida and Drouzas (1999)]. Upon drying, due to removal of water many physical changes (including mechanical strength) of biological product occur.

Numerous publications indicate that drying strongly affects rheological properties of the dried material. Wet materials are viscoelastic, while at low water content they become brittle, hence rheological properties of dried product are related either to water content or water activity [Gabas Menegalli, Ferrari and Talis-Romero (2002); Krokida Karathanos and Maroulis (2000); Krokida Maroulis and Marinos-Kouris (1998); Lewicki and Lukaszuk (2000)].

There are a few numerical studies that investigated the effect of product deformation, which involves modeling of coupled heat and mass transfer and stress. Hassini Peczalski, Azzouz and Belghith (2009) have investigated numerically and analyzed the distribution of temperature, moisture, strain, and stress of a shrinkable product during drying in 1-dimensionnel.

The purpose of the present study is to develop a tow- dimensional mathematical model able to predict the temperature and moisture content as well as the deformation behaviour of apple during drying. The model consists of coupled heat conduction and mass diffusion equations along with the solid mechanics equations. Governing equations as well as initial and boundary conditions are solved numerically using the Finite Elements method through using COMSOL Multiphysics software (version 3.3a). Drying is conducted at air temperatures of 40, 50, 60 and 70°C, a velocity close to 1.5 m.s⁻¹ and at relative humidity of 20% in a convective dryer [Toujani, Hassini, Azzouz and Belghith (2012)].

2 Modelling

2.1 Assumptions

Owing to obtain a closed set of governing equations of heat and mass transfer in cut apple, the following assumptions considered: (a) the apple material consisted of non compressible solid (dry matter) and liquid (water) phases, (b) the liquid vaporized only at the surface of the sample, (c) the shrinkage is ideal and isotropic, (d) the mechanical behavior of the material is viscoelastic and (e) the deformation is plane over the (x,y) plane and the deformation is free in the z direction ($\epsilon_{zz} = 0$).

2.2 Heat and mass transfer equations

Heat and mass transfer simulation models consisted on the liquid phase diffusion/advection equation (Eq. 1) and the heat diffusion/advection equation (Eq. 2). The advective terms due to shrinkage are written using the solid matter velocity (u_s) which is the coupling variable between the hydro-thermal and mechanical equations. Such a velocity is determined by solving simultaneously the mechanical part of the model. The magnitude of hydric shrinkage is described by means of the volumetric dry basis hydro-contraction coefficient β .

$$\frac{1}{1+\beta X} \frac{\partial X}{\partial t} = \frac{\partial}{\partial x} \left(\frac{D}{1+\beta X} \frac{\partial X}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{D}{1+\beta X} \frac{\partial X}{\partial y} \right) - \frac{u_s^x}{1+\beta X} \frac{\partial X}{\partial x} - \frac{u_s^y}{1+\beta X} \frac{\partial X}{\partial y} \tag{1}$$

$$\frac{\rho_s(C_{ps} + XC_{pl})}{1+\beta X} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial T}{\partial y} \right) - \frac{\rho_s(C_{ps} + XC_{pl})}{1+\beta X} u_s^x \frac{\partial T}{\partial x} - \frac{\rho_s(C_{ps} + XC_{pl})}{1+\beta X} u_s^y \frac{\partial T}{\partial y} \tag{2}$$

In the case of our material, the thermal energy is transferred by conduction and is conveyed by the shrinking material. In the case of isotropic shrinkage, the coefficient β can be related to the linear wet basis hydro-contraction coefficient α , as follows:

$$3\alpha = \frac{V_s}{V_0} \beta \tag{3}$$

The value of parameter α was given by Hassini, Peczalski, Azzouz and Belghith (2007).

2.3 Initial and boundary conditions

The sample temperature and water content are considered initially uniform. The water is assumed to evaporate only at the top sample surface and to be removed by convection. The heat transfer at the top sample surface is also supposed to be convective. The heat and mass transfer at the bottom of the sample are considered nil. According to these hypotheses, the initial and boundary conditions for the present model are as follows:

– At $t = 0$: $X = X_0$; $T = T_0$ (4)

– For $t > 0$: $x = 0 \Rightarrow \frac{\partial X}{\partial x} = \frac{\partial T}{\partial x} = 0$ (5)

$$\left. \begin{aligned} k[a_w(X, T)P_{vsat}(T) - HR.P_{vsat}(T_a)] &= \frac{\rho_s}{1+\beta X} (-D \frac{\partial X}{\partial x}) \\ k[a_w(X, T)P_{vsat}(T) - HR.P_{vsat}(T_a)]L_v(T) &= -h(T - T_a) - \lambda \frac{\partial T}{\partial x} \end{aligned} \right\} : x=L(t) \quad (6)$$

$$\frac{\partial X}{\partial y} = \frac{\partial T}{\partial y} = 0 : y = 0 \quad (7)$$

$$\left. \begin{aligned} k[a_w(X, T)P_{vsat}(T) - HR.P_{vsat}(T_a)] &= \frac{\rho_s}{1+\beta X} (-D \frac{\partial X}{\partial y}) \\ k[a_w(X, T)P_{vsat}(T) - HR.P_{vsat}(T_a)]L_v(T) &= -h(T - T_a) - \lambda \frac{\partial T}{\partial y} \end{aligned} \right\} : y=e(t) \quad (8)$$

2.4 Momentum transfer and mechanical behaviour

The momentum conservation equation inside the medium can be written in the form of static mechanical equilibrium.

$$\nabla (\sigma_{ij}) = 0 \quad (9)$$

Besides, solid and semi-solid foods behave usually as viscoelastic materials, with elastic and a viscous component [Karathanos, Kostaropoulos and Saravacos (1994)]. The viscoelastic behaviour can be determined by stress relaxation tests [Bhattacharaya, Harma and Kaufman (1988)] or by dynamic (oscillatory) measurements [Anglea Karathanos and Karel (1993)]. Hence, the viscoelastic behaviour is investigated. The basic hereditary integral formulation for linear isotropic viscoelasticity is as follows [Coussy, (2004)]:

$$\sigma_{ij}(t) = \int_0^t K(t - \tau) - \frac{2}{3}G(t - \tau) \frac{\partial \epsilon_{kk}^m}{\partial \tau} \delta_{ij} d\tau + 2 \int_0^t G(t - \tau) \frac{\partial \epsilon_{kk}^m}{\partial \tau} \delta_{ij} d\tau \quad (10)$$

which are the functions of relaxation function also called the instantaneous Young modulus:

$$K(t) = \frac{E(t)}{3(1 - 2\nu)}, \quad G(t) = \frac{E(t)}{3(1 + \nu)}, \quad \frac{G(t)}{G_0} = \frac{K(t)}{K_0} = \frac{E(t)}{E_0}, \quad (11)$$

Moreover, in numerical solid mechanics, these equations are not solved in term of strain (ε) but in terms of displacements (u) in the x and y directions. The relations between displacement, strain rate tensor and solid phase velocity are given below.

$$\varepsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \quad i, j = x, y \quad (12)$$

$$\text{and } v_s^i = \frac{\partial u_i}{\partial t} \quad (13)$$

The drying process of porous wet medium without rigid solid matrix induces volumetric shrinkage which corresponds, in structural mechanics, to a strain imposed on the material. Such a strain is called hydro-strain (ε_h). Therefore, hydro-strain is subtracted from the total strain (ε_t) to get the total mechanical strain (ε_m) [Hassini, Peczkalski, Azzouz and Belghith (2009)]:

$$\varepsilon_m = \varepsilon_t - \varepsilon_h = \varepsilon_t - \alpha (X - X_0) \quad (14)$$

2.5 Parameters estimation

Various physical properties and transport parameters are required to solve the governing equations. These properties are determined experimentally and well cited in literature as summarized in the following:

- **Heat transfer coefficient (h):** used in the boundary conditions heat transfer treatment. Incropera and Dewitt (1996) gave the following relationship for h for a convective dryer:

$$h = 0.232 \frac{\lambda_a}{\bar{d}} \left(\frac{u_a \bar{d}}{\nu_a} \right)^{0.731} \text{Pr}^{0.35} \quad (15)$$

where u_a is the air velocity and \bar{d} is the sample width averaged over the entire drying time.

- **Convective mass transfer coefficient (k):** at the sample surface the coefficient k is calculated from the heat transfer coefficient according to the following formula [Peczalski and Laurent (2001)] as:

$$k = h / (65 L_v (T_h)) \quad (16)$$

- **Thermal conductivity (λ):** Apple thermal conductivity is given by Lewicki and Jakubczyk (2004) as:

$$\lambda = 0.567 \quad (17)$$

- **Specific heat (C_p):** the specific heat (C_p) of apple is also given by Lewicki and Jakubczyk, (2004):

$$C_p = 3.683 \quad (18)$$

- **Latent heat of water evaporation (L_v):** the latent heat of water evaporation (L_v) is also given by Lewicki and Jakubczyk (2004):

$$L_v (T) = 2495.46 + 1881 (T_a - 273) - 4180 (T - 273) \quad (19)$$

- **Moisture diffusion coefficient (D):** the moisture diffusion coefficient (D) is given by the correlation adopted by Azzouz, Guizani, Jomaa and Belghith (2002) and Hassini, Azzouz, Peczkalski and Belghith (2007), it is written as:

$$D(X, T) = D_0 \exp\left(-\frac{E_a}{RT}\right) \exp[-(AT + B)X] \quad (20)$$

where A and B are the constants. In this study, these constants are obtained by fitting the simulated results to the experimental results at various drying conditions. As a result, D is found to be:

$$D(X, T) = 0.0024 \exp\left(-\frac{37.0280}{RT}\right) \exp[-(-0.0005T + 0.2802)X] \quad (21)$$

- **Equilibrium moisture content (X_e):** the equilibrium moisture content (X_e) of apple is determined through the moisture sorption isotherm [Toujani, Hassini, Azzouz and Belghith (2011) and (2012)]:

$$X_e = A a_w^B + C a_w^D \quad (22)$$

where A, B, C and D are the empirical constants listed in Table.1.

Table 1: Empirical constants of (Eq. 22) at different drying temperatures.

Temperature (°C)	A	B	C	D	R ²
50	0.0731	0.2791	0.8932	3.4204	0.9877
70	0.0453	0.2438	0.6703	3.8497	0.9971

- **Volume and linear shrinkage coefficient (β, α):** The volume and linear shrinkage coefficient which appears in model equations is defined as the relative sample volume and thickness change over the corresponding moisture content change. The

experimental data were then fitted by the following linear equation [Hassini, Azzouz, Peczalski and Belghith (2007)]:

$$\frac{V}{V_0} = \frac{V_s}{V_0}(1 + \beta X) \tag{23}$$

where V_s is the final (dry) product volume, V_0 is the initial product volume and the volume shrinkage coefficient is calculated from the best fit slope.

The linear shrinkage coefficient α is determined using Eq. 3.

- **Density (ρ):** the apple density (ρ) is determined experimentally and correlated with the moisture content through the following equation [Hassini, Azzouz, Peczalski and Belghith (2007) and Toujani (2013)]:

$$\rho = c_s + c_l = \rho_s \frac{(1 + X)}{(1 + \beta X)} \tag{24}$$

where $\rho_s=650.47 \text{ kg m}^{-3}$ is the intrinsic solid density and $\beta=0.672$ is the hydric expansion coefficient.

- **Relaxation function and Poisson’s ratio:** Relaxation function $E(t)$ and Poisson’s ratio (ν) are determined experimentally to a single sample of apple by a compressive- relaxation test using a numerical command traction/compression machine. The compression is made by a piston of velocity 10 mm/min and completed at 20% deformation of the initial apple thickness. The measurements are repeated 10 times which leads to the following correlation [Yang, Sakai and Watanable (2001)]:

$$E(t) = E_0 + \sum_{1,2} E_i \exp(-t/\tau_i) \tag{25}$$

Poisson’s ratio (ν) of apple is assumed to be constant and equal to 0.33 in all cases (Yang, Sakai and Watanable, 2001). The fitting results are given in Table 2.

Table 2: Fitting results of the experimental relaxation function with a Prony series.

i	E_i (MPa)	τ_i (s)	η_i (MPa.s)
0	0.1773	-	-
1	0.2735	18.2720	4.9974
2	0.5897	1.6276	0.9260

2.6 Model implementation

Thanks to the symmetry of the problem (Fig. 1), the above described model is solved on two-dimensional plane spanning over the half ($5\text{mm} \times 10\text{mm}$) of apple sample cross-section. Therefore, numerical simulation is of practical use in such complex multi-physic problem; COMSOL-Multiphysics is one of the most popular and powerful tool among a large variety available for engineering and industrial applications. This tool is employed to tackle multi-physic problems based on finite elements approach using a set of elementary solvers that can be coupled in various ways. In the present study, the governing equations as well as initial and boundary conditions are numerically implemented by means the COMSOL Multiphysics finite-elements software (version 3.3a) using both the ‘Chemical Engineering’ and the ‘Structural mechanics’ modules. The computational mesh is defined by means of triangular elements. The direct (UMFPACK) linear system solver is used.

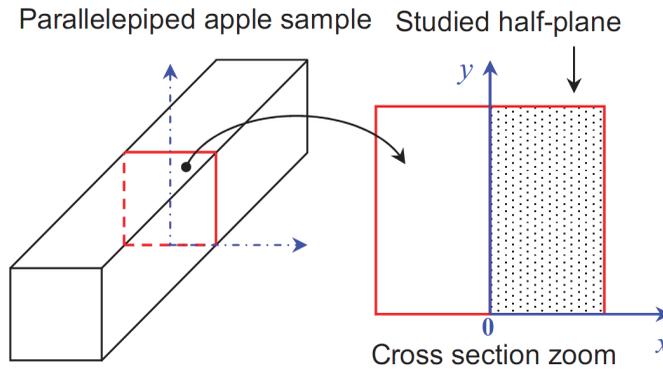


Figure 1: Model configuration: a half-plane is considered.

3 Results and discussion

The simulated results, in terms of the moisture content and temperature are compared with the experimental results. Besides, during the convective drying the principal stress and moisture gradient profiles of apple sample are presented to understand the drying phenomenon steps.

3.1 Hydro-thermal model validation

In order to validate the hydro-thermal part of the developed model, several tests are carried out for different drying temperature values at relative humidity 0.2 and air velocity close to 1.5m/s. A parallelepiped apple sample of dimensions:

$30 \times 10 \times 10 \text{ mm}^3$ is chosen to be tested. It is worth to mention that apple material presents some advantages such as homogeneity, isotropy of thermal and mass properties, high initial moisture content and high hydro shrinkage coefficient. Apple properties used for the simulation are given procurement. The apple slabs were placed the waterproof side down on a horizontal perforated tray which was suspended to a digital balance, the balance being placed outside the drying chamber. The dryer worked in closed loop. The mean free-stream temperature in the dryer was set at 40, 50, 60 and 70°C with $\pm 1^\circ\text{C}$ of uncertainty. The drying tunnel, designed and manufactured in the LETTM laboratory-Faculty of Science of Tunis, is of vertical type with full control of the drying air parameters: temperature, velocity and relative humidity. The dryer layout is given in previous work [Toujani, Hassini, Azzouz and Belghith (2012)].

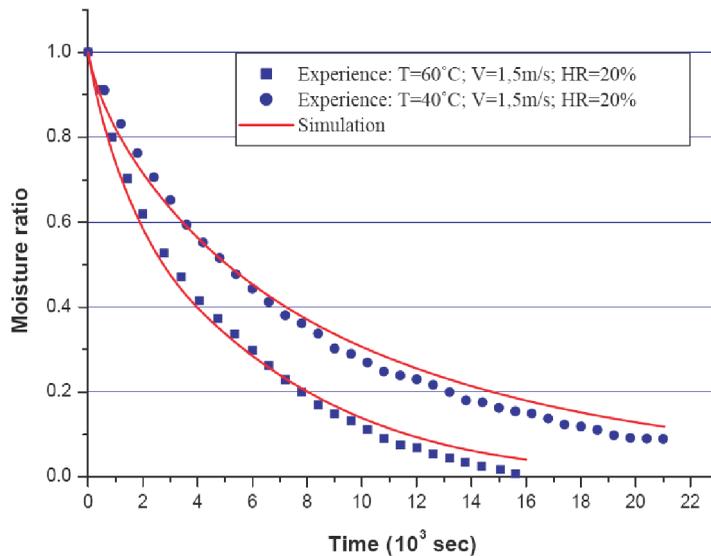


Figure 2: Comparison between simulated and experimental moisture content of apple.

Figures 2 and 3 compare simulated and experimental moisture content of apple undergoing convective drying at different drying temperatures. During drying moisture in apple body migrated from inside to the surface of product and the rate of moisture movement is depicted partially by the diffusivity and partially by the mass transfer boundary conditions at the apple surface. It can be seen in Figs. 2 and 3 that the moisture decreases quickly at higher temperatures because the temperature differences between the samples and the drying air at higher drying temperatures

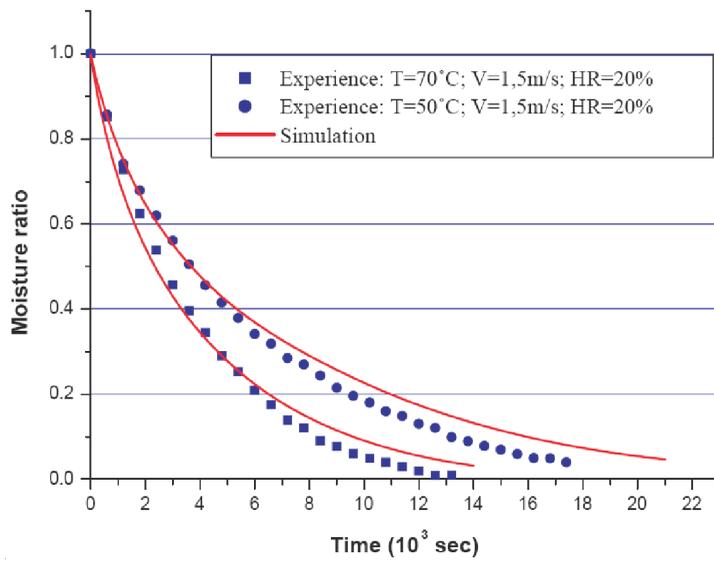


Figure 3: Comparison between simulated and experimental moisture content of apple.

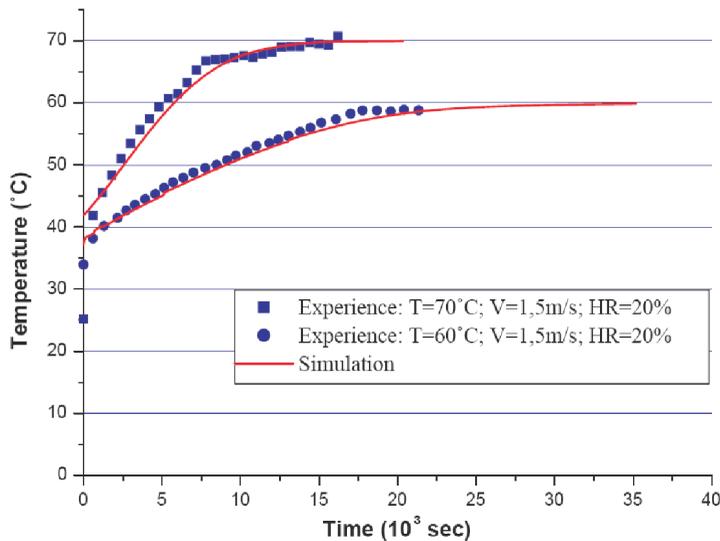


Figure 4: Comparison between simulated and experimental product temperature.

are greater than those at lower temperatures, and the moisture diffusion coefficient is higher at a higher temperature. The experimental and numerical results illustrate the absence of constant drying period and drying takes place only in the falling rate period. This indicates that diffusion is the most likely physical mechanism governing moisture movement in the apple. It is found that the moisture content predictions are in very good agreement with the experimental data.

Representative temperature profiles of apple over time are also presented in Fig. 4. During drying, heat is transferred from the drying air to the sample surface by convection, then to its inside body by conduction. The temperature change is depicted by the thermal properties of apple as well as the heat transfer at boundaries. The product temperature increases rapidly during the first period of drying. Then, the temperature increases slowly, while latent heat of evaporation prevents rapid temperature rise. It is found that the profiles of the temperature prediction are in good agreement with the experimental results.

According to Figs 2, 3 and 4, there is an acceptable agreement between the experimental and predicted results. For all drying conditions, the relative difference between the experimental drying time and the simulated ones is less than 10%, which is satisfactory [Youssef-Ali, Moumami, Demons, Abene, Messaoudi and Le Ray, (2001)]. The slight misfit observed can be attributed in part to measurements errors, especially in the mass record due to the support vibration generated by the airflow and in the temperature record due to the imprecision of thermocouple positioning at the centre of the sample. In the other part, the discrepancy is due to the simplifying assumptions of the model such as using ideal isotropic shrinkage model.

3.2 Simulation of the mechanical behaviour

The distribution of mechanical stress within the sample at drying times of 0.5, 2 and 5 hours are presented respectively in Figs. 5 and 6. The presented stress distributions, are determined for (x,y) plane at the middle length of the sample. Conventionally, the positive and negative stress values correspond to tensile and compressive stresses respectively. According to our results, the superficial sample layer -in contact with hot air- is in traction while the core of the sample is in compression.

The initial stress rise is due to water content gradient build-up: the stronger the moisture gradient is, the stronger is the stress. The superficial layer of the sample, which is in direct contact with hot air, is thus the more solicited. According to our simulations, the normal stress in the x -direction at the upper sample surface is higher than the normal stress on the lateral surface all over the drying process, so that the cracks are more possibly to appear at the top of the sample. However, these

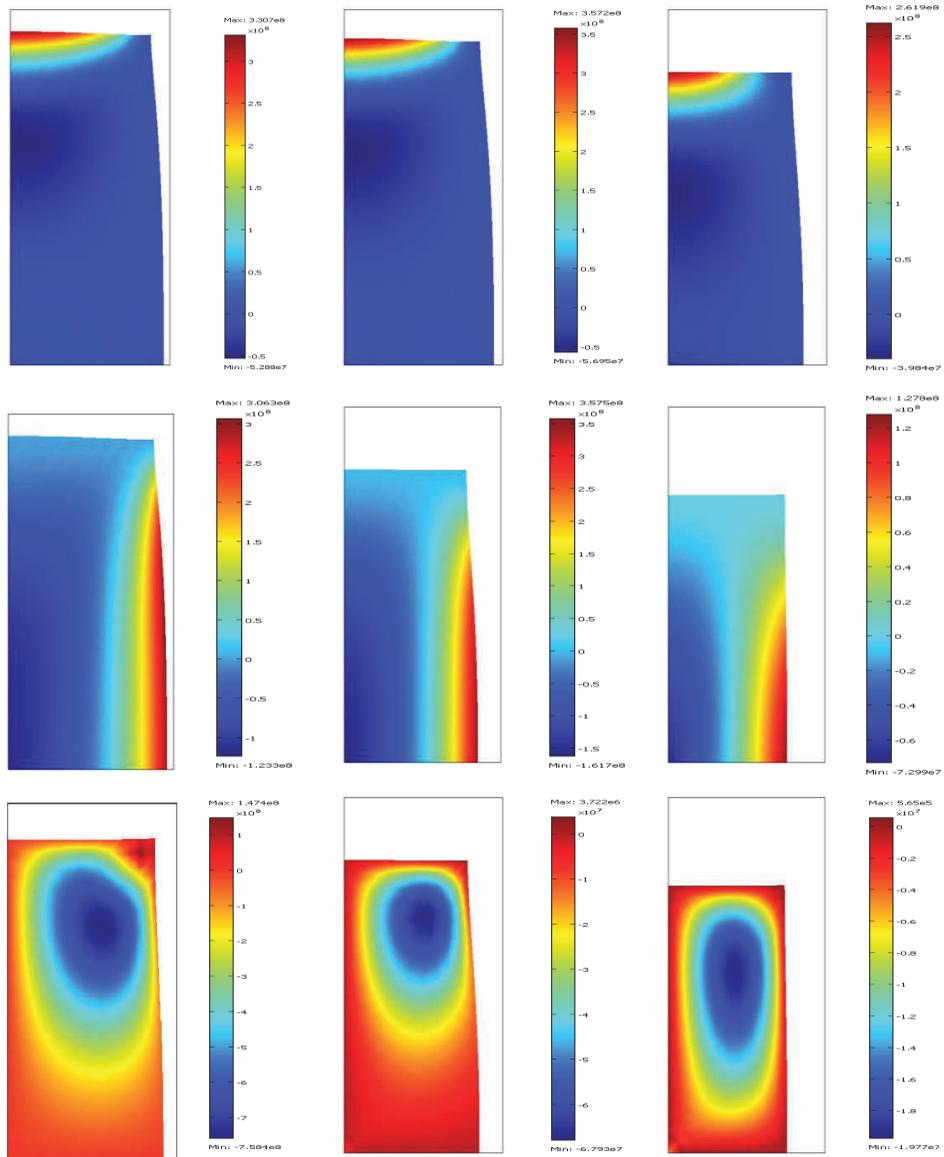


Figure 5: Distributions of normal stress σ_{xx} (top) in the x-direction, normal stress σ_{yy} in the y-direction and shear stress σ_{xy} (bottom) in the (x,y) plane at drying time 0.5h (left), 2h (middle) and 5h (right) and $T = 50^\circ\text{C}$, $V = 1.5 \text{ m/s}$, $\text{RH} = 20\%$.

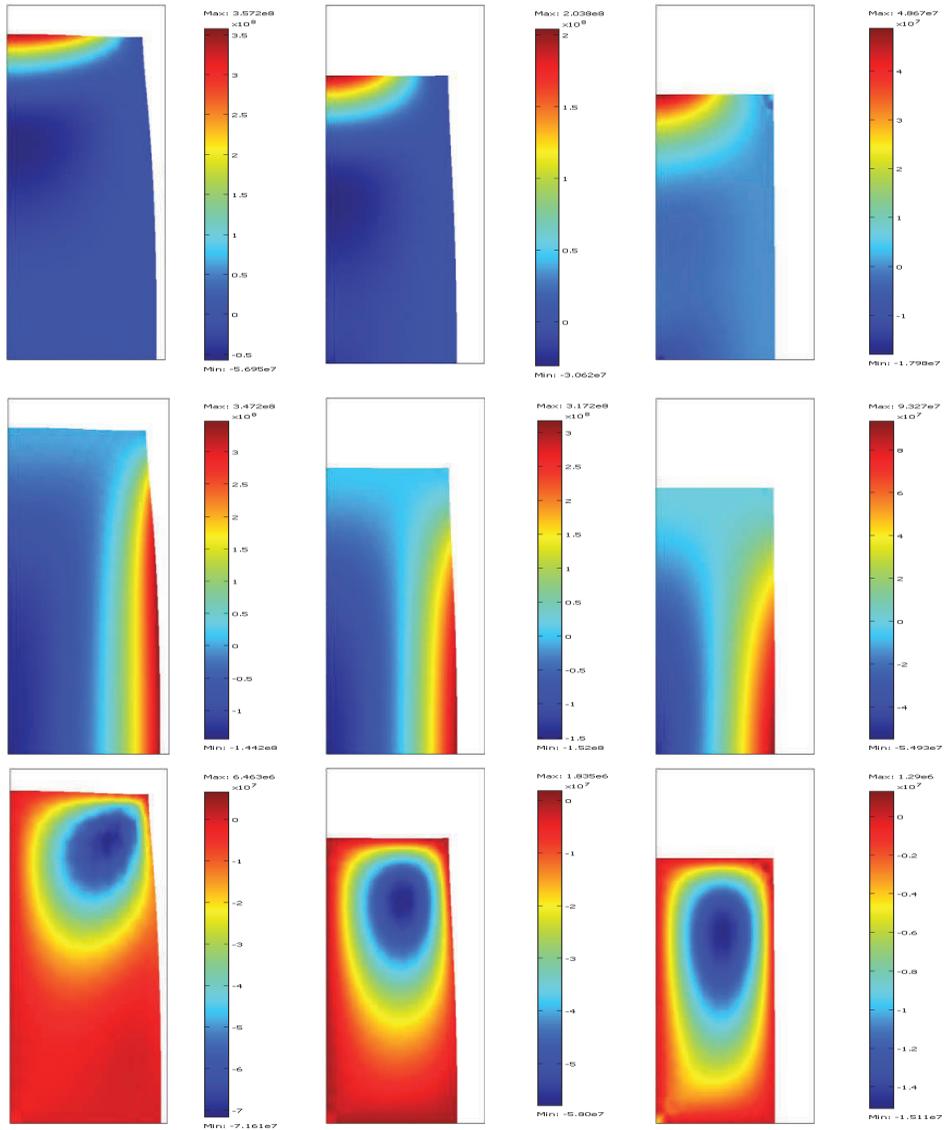


Figure 6: Distributions of normal stress σ_{xx} (top) in the x-direction, normal stress σ_{yy} in the y-direction and shear stress σ_{xy} (bottom) in the (x,y) plane at drying time 0.5h (left), 2h (middle) and 5h (right) and $T = 70^\circ\text{C}$, $V = 1.5 \text{ m/s}$, $\text{RH} = 20\%$.

cracks, if it exists, could not expand into the lower part of the sample because it is in compression. This result is similar to former findings of Kowalski and Rajewska (2002), Rémond (2007) and Hassini, Peczalski, Azzouz and Belghith (2009) in the case of convective drying of cylindrical kaolin sample of a wooden board and of a parallelepiped potatoes sample.

During drying the material undergoes shrinkage. In the early stages of drying the surface layers properties do not differ much from those in the sample core. The apple material is assumed to be viscoelastic and is able to deform. The amount of evaporated water is reflected by change in volume. Hence, the material shrinks and the shape can be substantially changed.

Besides, the shrinkage of the sample generates a negative shear stress in the sample with a maximum value in the corners, which entrain the degradation of its right angles. It can be observed that the maximum principal tensile stress in dried product at 70°C is higher than that at 50°C. This is certainly due to clearance of more water if drying temperature is 70°C, which causes more shrinkage, thus strains and stresses are more intense. The similar trend occurs in the case of maximum principal compression stress. This corresponded to the effect of drying temperature on both product shrinkage and maximum moisture gradients. This phenomenon goes well with observations presented by Niamnuy, Devahastin, Soponronnarit and Raghavan (2008).

4 Conclusion

Governing equations of hydro-thermo-viscoelastic material are formulated to simulate transient two-dimensional heat and mass transfer and mechanical stress during drying of parallelepiped apple sample in a laboratory air-dryer. The comparison between predicted and experimental values of temperature and moisture content for the hydro-thermal model shows that the present mathematical model gives acceptable results. Moreover, the model is used to simulate the internal mechanical strains and stresses induced by water removal. It was found, that the maximum stress arises at the beginning of drying and hold at the top external surface of the sample which is the surface facing the airflow, which agrees well former findings.

In our future works we'll introduce the Taguchi experimental design technique since the drying processes are of great complexity due to the various parameters and are of great importance due to quality control. This method is characterized by a significant reduction in the number of tests while maintaining good accuracy, is required in the industrial practice of experiments design and has met with growing interest in engineering process [Djebali, Toujani and Pateyron (2013)]. The key idea of this technique is that it treats jointly the parameters average that govern the

system (product or process) and the dispersion (noise) of these parameters. The optimal parameter combination of multi-response is finally justified by a confirmation test.

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