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Apple convective drying - Part I: Finite elements parametric study for appraising the operating conditions effects

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ABSTRACT

Drying of biomaterials such as agro-food products includes mass, momentum and energy transport coupled with shrinkage of the porous material which have important impacts on the final quality and energy consumption. These materials present non-linearity when going through deformations that affect the transport process in critical way. Therefore, it's important to realize a finite element modeling and simulation of this phenomenon. In this paper apple convective drying process is investigated. The hydro-thermo-viscoelastic behavior of this phenomenon is modeled and simulated using COMSOL Multiphysics. The grid independency test is checked and the validation of the model is performed by comparing the present results with former predictions and measurements for temperature and water content time evolution under conditions: T = 50-70 °C, V = 1.5 m/s and HR = 20%. The present results show good agreement with reference predictions and measurements. The aim of the study is to analyze the influence of some of the most important operating factors, namely humidity, temperature and velocity of the drying air on the performance of drying process of an apple slice.

Keywords:
Finite element modeling and simulation; agro-food convective drying process; hydro-thermo-vischavioroelastic behaviour, apple slice.

1. Introduction

To reduce energy consumption and to obtain a good quality of the product, the control and optimization of the drying process is required. To do that, knowing the temperature and the water content distributions in addition to the mechanical behavior as a function of the operating conditions used is required. Generally, food products are considered as porous rigid media. Simulating the drying process is a complicated problem, since the phenomena takes into account many physics including heat transfer, diffusion, transportation of liquid water and the shrinkage. Inadequate drying of fresh fruit or vegetable leads to high levels of water activity which reduce the

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shelf life and can cause deterioration, leading to food safety hazards. For the time / energy issue, a dramatic upsurge in interest in drying world-wide has been marked -due to the sharp rise in energy costs- has promoted over the last decade.

Drying of fruits takes usually long time to evaporate the remaining water. However, over-drying can cause excessive energy consumption. In addition, since the dried products are brought into ambient environment, removing completely the moisture content is not required. In fact, ambient environment generally processes packages and stores lower temperatures and often higher humidity.

Therefore, stopping drying little earlier can save energy and allow to develop more intelligent drying processes. From a mechanical point of view, the dehydration includes the shrinkage. So, if the dehydration is partial, than probably, it's not possible to get the desired shrinkage. Accordingly, the drying time affects the quality of fruit and the approval of the consumer.

Several agro-industrial and agro-food drying studies has been conducted. In some, authors have investigated the impact of different parameters, including drying air temperature, velocity, humidity, sample size and environmental conditions [1,2]. Others are interested to treat control strategies [3], the spatial heterogeneity of water content in samples during drying [4, 5] or the energetic drying problem by searching for more energetically beneficial processes, including intermittent drying [6, 7].

Yet, in most incidences, full dehydration has been inspected and it was concluded that the drying time was practically the same for all cases even though some samples dried out quicker than others. Author mentioned that the determination of appropriate downtime needs measurements of water activity after stabilizing which is the appropriate parameter to determine if the fruit is sufficiently dried or not and guarantee food safety and adequate shelf life. Measurement of water activity and moisture content at different times during the drying is tedious. Besides, water activity and moisture content are related via the sorption isotherms. The moisture content is generally controlled by gravimetry in drying studies as a criterion for evaluating whether drying process is achieved.

Analysis of literature [1, 8-13] shows that rheological properties of the dried material are highly affected by drying. Humid materials are visco-elastic and become fragile when water is low. Rheological properties of dried products are, thus, related to moisture content or water activity.

Some numerical studies were concerned with the impact of product deformation, including the modelling of three physics: heat and mass transfers and mechanical stresses. Toujani *et al.,* [14] and Hassini *et al.,* [9] studied numerically the temperature distributions, moisture, deformation and mechanical stress of a shrink product in two-dimensional drying by considering plan deformation, visco-elasticity and isotropic water shrinkage. They considered only solid and liquid phases and concluded that the maximum stress takes place at the start of the drying at the top surface confronting the flow and the drying phenomenon is enhanced by the temperature. From an energy point of view, the study of T. Defraeye [15] was conducted with more sense by asking the downtime of the drying process before total dehydration.

However, this depends on the case. The effect of when stopping drying is not taken into account in most studies. T. Defraeye [15] mentioned that the determination of appropriate downtime needs measurements of water activity after stabilizing which is the appropriate parameter to determine if the fruit is sufficiently dried or not and guarantee food safety and adequate shelf life. Zlatanovi *et al.,* [16] investigated the effects of temperature, relative humidity, velocity, and size of thin-film apple cubes on the drying process. They concluded that the time needed to achieve moisture balance from the initial moisture content increases by rising the drying air temperature and velocity and reducing the relative humidity and the sample size.

Some researchers investigated the impact of drying techniques to determine optimal performance and yield. Hafiz Majid and Hadassah Alau Rining [17] conducted a comparative study of three different drying techniques namely freeze, oven and sun drying, in order to figure out which method is best for preserving the highest amount of total phenolic and flavoid content and they established that freeze drying is the best technique.

S. Suwastia *et al.,* [18] focused on the influence of using four types of fin on the performance of shelf type solar dryer and they found that the small wave fin gave the lowest optimum performance. Arina Mohd Noh *et al.,* [19] simulated and analyzed the impact of different drying conditions on the temperature and the distribution of the air flow inside the drying chamber of solar dryer and concluded that the highest temperature was produced using operating conditions with intermittent active ventilation.

In this paper, a numerical model to solve the coupled heat and mass transfers and mechanical behavior for rectangular apple has been proposed and the influence of the operating parameters (temperature, velocity and the humidity of the drying air) on the residual mechanical stresses and drying time has been discussed.

2. Modeling

2.1. Numerical method

The present study is a complex multi-physic problem; subsequently, numerical simulation is of practical exploit. The COMSOL-Multiphysics software is used as a powerful tool of modeling and simulation of engineering and industrial applications involving several physics couplings. This tool is used to solve multiple physic problems based on the approach of finite elements using a set of elementary solvers that can be combined in different ways. In this study, the governing equations and initial and boundary conditions are numerically implemented by means of COMSOL Multiphysics (v. 4.3). Triangular elements are used to define the computational mesh with refinement near walls involving high properties gradients.

2.2. Model implementation and assumptions

In this work, a FE modeling and simulation has been carried out. The model consists of coupled heat conduction and mass diffusion equations along with the solid mechanics equations. Initial and boundary conditions are numerically implemented by means of COMSOL Multiphysics finite elements software using the modulus of "heat transfer in porous media", "Transport of diluted species" and "Structural mechanics". Drying is carried out at air temperatures of 40, 50, 60 and 70 °C, a velocity close to 1.5 m/s and a relative humidity of 20% in a convective dryer [14]. A symmetric geometry 2D (5mm x 10 mm) of a 3D apple sample is considered in the simulation (Figure 1). The heat and mass transfer conditions is applied at all boundaries except at the limit of symmetry (y=0). The following assumptions are considered:

a) Porous media, triphasic, incompressible solid and liquid (water) phases and vapor,
b) Homogenous material,
c) The liquid is vaporized at the surface of the sample,
d) In the initial state, the temperature and humidity of the sample are uniform,
e) Shrinkage is anisotropic,
f) Viscoelastic behavior,
g) Plane deformation according to the plane (x, y) and free deformation in the z direction,

h) The environment obeys small disturbances.

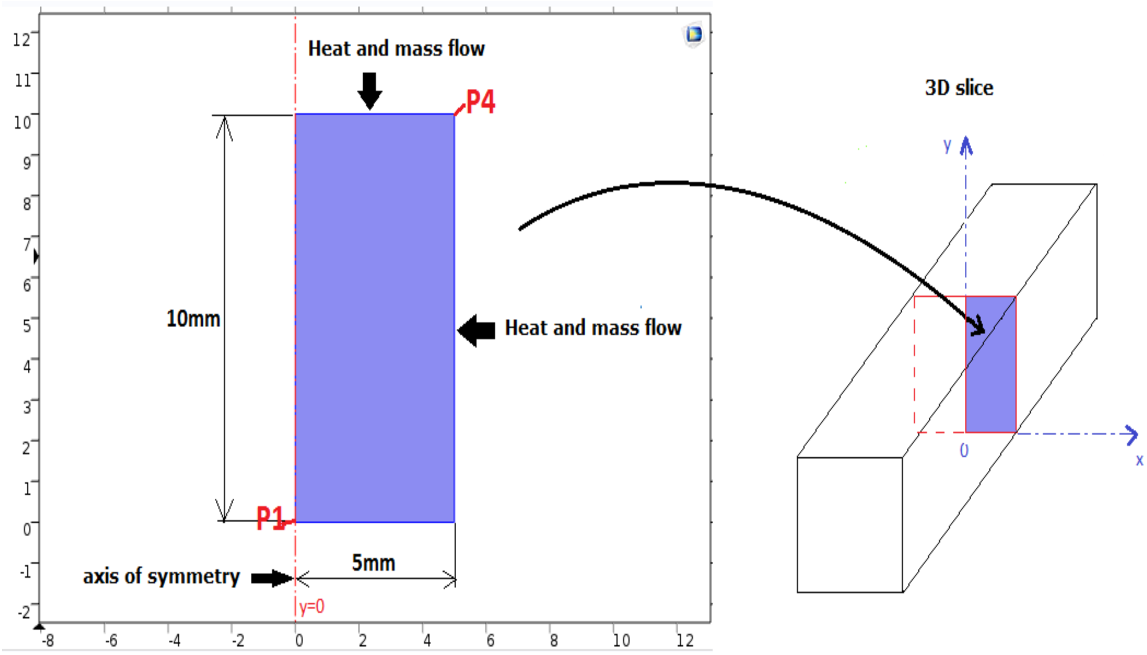


Fig. 1. Model configuration: a rectangular half plan is considered.

2.3. Governing equations

The problem governing equations consist of the heat and mass transfer equations, initial and boundary conditions and the momentum transfer and mechanical behaviour.

2.3.1. Heat and mass transfer equations

The heat and mass transfer simulation models included the equation of the diffusion / advection in the liquid phase (Eq. 1) and the equation of diffusion / thermal advection (Eq. 2).

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

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

2.3.2. Initial and boundary conditions

$$\text{At } t=0\,; \quad X=X_0\;;\quad T=T_0 \tag{3}$$

$$\text{A } t>0; \quad x=0\ \Rightarrow \frac{\partial X}{\partial x}=\frac{\partial T}{\partial x}=0\ ; y=0\Rightarrow\frac{\partial X}{\partial y}=\frac{\partial T}{\partial y}=0 \tag{4}$$

$$\text{At } x=L(t)\begin{cases}\dfrac{\rho_s}{1+\beta X}\left(-D\dfrac{\partial X}{\partial r}\right)\Big|_L=k[a_w(X,T)P_{vsat}(T)-HR.P_{vsat}(Ta)]\\(-\lambda\dfrac{\partial T}{\partial r})\Big|_L-k[a_w(X,T)P_{vsat}(T)-HR.P_{vsat}(Ta)]L_v(T)=h(T-T_a)\end{cases} \tag{5}$$

$$At\ y = e(t), \begin{cases} \frac{\rho_s}{1+\beta X}\left(-D\frac{\partial X}{\partial z}\right)\Big|_e = k[a_w(X,T)P_{vsat}(T) - HR.P_{vsat}(Ta)] \\ (-\lambda\frac{\partial T}{\partial z})\Big|_e - k[a_w(X,T)P_{vsat}(T) - HR.P_{vsat}(Ta)]L_v(T) = h(T - T_a) \end{cases} \quad (6)$$

2.3.3. Momentum transfer and mechanical behaviour

$$\nabla(\sigma_{ij}) = 0 \quad (7)$$

$$\sigma_{ij}(t) = \int_0^t K(t-\tau) - \frac{2}{3}G(t-\tau)\frac{\partial\varepsilon_{kk}^m}{\partial\tau}\delta_{ij}d\tau + 2\int_0^t G(t-\tau)\frac{\partial\varepsilon_{kk}^m}{\partial\tau}\delta_{ij}d\tau \quad (8)$$

$$K(t) = \frac{E(t)}{3(1-2\upsilon)}; \quad G(t) = \frac{E(t)}{3(1+\upsilon)}\ ; \ \frac{G(t)}{G_0} = \frac{K(t)}{K_0} = \frac{E(t)}{E_0} \quad (9)$$

$$\varepsilon_{ij}(t) = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\ ; i,j = x,y \quad (10)$$

Where $u_s^i = \frac{\partial u_i}{\partial t}$ $and\ \varepsilon_m = \varepsilon_t - \varepsilon_h = \varepsilon_h - \alpha(X - X_0)$ (11)

2.4. Parameters estimation and hydro-thermo-viscoelastic properties

Numerous physical properties and transport parameters are required to solve the governing equations. These properties are empirically identified and well cited in the literature as summarized in the Table 1 [14-15, 20-22]. Also, COMSOL Multiphysics library data is considered. It should be noted that apple material has some features such as homogeneity, isotropy of thermal and mass properties, high rate of both coefficients of hydraulic shrinkage and initial moisture content.

Table 1. Hydro-thermo-viscoelastic properties of the apple and initial conditions

<table>
<tr><th>Properties</th><th>Expressions</th></tr>
<tr><td>Poisson coefficient ν</td><td>0.33</td></tr>
<tr><td>Young's modulus E</td><td>$E(X) = 0.5222 + 0.00048\,e^{(1.728X)}$</td></tr>
<tr><td>Relaxation modulus G</td><td>$G = \frac{E}{3(1+\upsilon)}$</td></tr>
<tr><td>Conservation modulus K</td><td>$K = \frac{E}{3(1-2\upsilon)}$</td></tr>
<tr><td>Relaxation function $E(t)$</td><td>$E(t) = E_0 + \sum_{i=1}^{2} E_i.e^{-t/\tau_i}$
<table>
<tr><th>i</th><th>$E_i(MPa)$</th><th>$\tau_i(s)$</th><th>$\eta_i(MPa.s)$</th></tr>
<tr><td>0</td><td>0,1773</td><td>-</td><td></td></tr>
<tr><td>1</td><td>0,2735</td><td>8.272</td><td>4,9974</td></tr>
<tr><td>2</td><td>0,5897</td><td>1,6276</td><td>0,926</td></tr>
</table></td></tr>
<tr><td>Volumetric mass density</td><td>$\rho(X) = \frac{-45.27 + 45.60\,X^{0.00069}}{0.00043 + X^{0.00069}}$</td></tr>
<tr><td>Density</td><td>$\rho = c_s + c_l = \rho_s\frac{(1+X)}{(1+\beta X)}$ where $\rho_s = 650.47\ [kg.m^{-3}]$ and $\beta = 0.672$</td></tr>
<tr><td>Thermal conductivity</td><td>$\lambda = 0.567[\,W.m^{-1}.K^{-1}]$</td></tr>
<tr><td>Heat capacity</td><td>$C_p = 3.683[\,kJ.kg^{-1}\,.°C^{-1}]$</td></tr>
</table>

<table>
<tr><td>Latent heat</td><td>$Lv(T) = 2495.46 + 1881(T_a - 273) - 4180(T - 273)J.kg^{-1}$</td></tr>
<tr><td>Water diffusivity</td><td>$D(X,T) = D_0 \exp\left(-\frac{E_a}{RT}\right)\exp[-(AT+B)X]$
<table>
<tr><td>$D_0 = 0.00241$</td><td>$E_a = 37.028$</td></tr>
<tr><td>$A = 0.00051$</td><td>$B = 0.28022$</td></tr>
</table></td></tr>
<tr><td>Coefficient of heat transfer</td><td>$h = 2.\frac{\lambda}{L}\frac{0.3387(Pr^{1/3}Re^{1/2})}{\left(1+\left(\frac{0.0468}{Pr}\right)^{\frac{2}{3}}\right)^{\frac{1}{4}}}\ for\ Re < 5.10^5\ and\ Re = \frac{Vair.L}{\lambda}$</td></tr>
<tr><td>Mass fraction of vapor</td><td>$w_v = 0.026$</td></tr>
<tr><td>Initial moisture content</td><td>$w_{m,ini} = 780\ [\mathrm{kg/m^3}]$</td></tr>
<tr><td>Porosity</td><td>0.25 (average value)</td></tr>
<tr><td>Equilibrium water content</td><td>$X_e = Aa_w^B + Ca_w^D$
<table>
<tr><th>T(°C)</th><th>A</th><th>B</th><th>C</th><th>D</th><th>R^2</th></tr>
<tr><td>40</td><td>0.12193</td><td>0.35014</td><td>1.23205</td><td>4.44941</td><td>0.99745</td></tr>
<tr><td>50</td><td>0.07275</td><td>0.17532</td><td>1.01793</td><td>3.50458</td><td>0.99025</td></tr>
<tr><td>60</td><td>0.0731</td><td>0.2791</td><td>0.8932</td><td>3.4204</td><td>0.9877</td></tr>
<tr><td>70</td><td>0.0453</td><td>0.2438</td><td>0.6703</td><td>3.8497</td><td>0.9971</td></tr>
</table></td></tr>
<tr><td>Permeability</td><td>$\kappa = 4e^{-12}[m^2]$</td></tr>
<tr><td>Initial concentration of apple moisture content</td><td>$C_0 = \frac{\mathrm{w_m}}{M_w} = 780/18.016\mathrm{e}^{-3} = 43294.84[mol/m^3]$</td></tr>
<tr><td>Molecular weight of water</td><td>$M_w = 18{,}016[g/mol]$</td></tr>
<tr><td>Initial temperature of apple</td><td>$T_0 = 20[°C]$</td></tr>
<tr><td>Initial moisture content (dry</td><td>$X_0 = 6\ [kg - \mathrm{water}/kg\ ms]$</td></tr>
<tr><td>Initial fraction of apple water</td><td>$Y_w = 0.881$</td></tr>
<tr><td>Heat capacity of liquid water</td><td>$C_{pl} = 4182[\mathrm{J/(kg.K)}]$</td></tr>
<tr><td>Heat capacity of water vapor</td><td>$C_{pv} = 1880[\ \mathrm{J/(kg.K)}]$</td></tr>
<tr><td>Sorption isotherm</td><td>$w_m(\mathrm{a_w}) = \mathrm{w_s}\left(\frac{0.15926}{\ln\left(\frac{1.0177}{\mathrm{a_w}}\right)}\right)^{\frac{1}{0.97014}}$</td></tr>
<tr><td>Convective mass transfer coefficient during drying</td><td>$h_{cm} = 7.03.10^{-7}\ [\mathrm{s.m^{-1}}]$</td></tr>
</table>

3. Numerical results

3.1. Grid independency test and hydro-thermal model validation

The grid independency test is checked for extreme conditions (T = 70 °C, V = 1.5 m/s and HR = 20%) For the grid resolution, normal mesh, fine mesh, more fine mesh and extra fine mesh sizes of respectively 444, 581, 925, 2330 nodes corresponding to 560, 774, 950 and 3812 elements. The converged values are compared to reference results as presented in Figure 2.

There is a rationally good accordance between the simulated results and those obtained by Toujani *et al.,* [14]. The comparison between the simulated curves and those predicted by the Toujani et al. the time evolution of the temperature inside the sample for a drying temperature T = 70 °C and T = 50 °C is presented in Figure 3. The comparison of evolution of the temporal difference in water content is presented in Figure 4. It may be concluded from Figure 3 and 4 the excellent agreement between the results of the present model and reference experimental and numerical ones. The observed disparities can be attributed in part to the cumulative imperfections of the experiment. It should be pointed out that the model hypothesis, notably the anisotropic shrinkage hypothesis, can also explain the differences observed on the comparison curves.

Note that the temperature increases until reaching a constant value corresponding to the drying air temperature. The result reflects the fact that the internal transfer of water in the product is limited. In addition, during drying, the loss of water is more pronounced at the surface than inside the sample, because of the high water gradient in this region. At the end of the drying, the gradient of the water content becomes very low throughout the sample section and the moisture reaches its equilibrium value with the drying air.

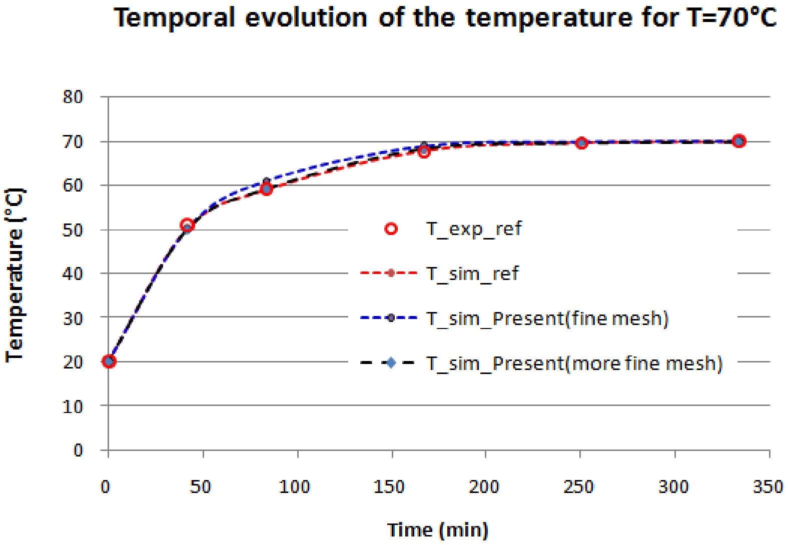


Fig. 2. Checking the grid independency for extreme conditions (T = 70 °C, V = 1.5 m/s and HR = 20%).

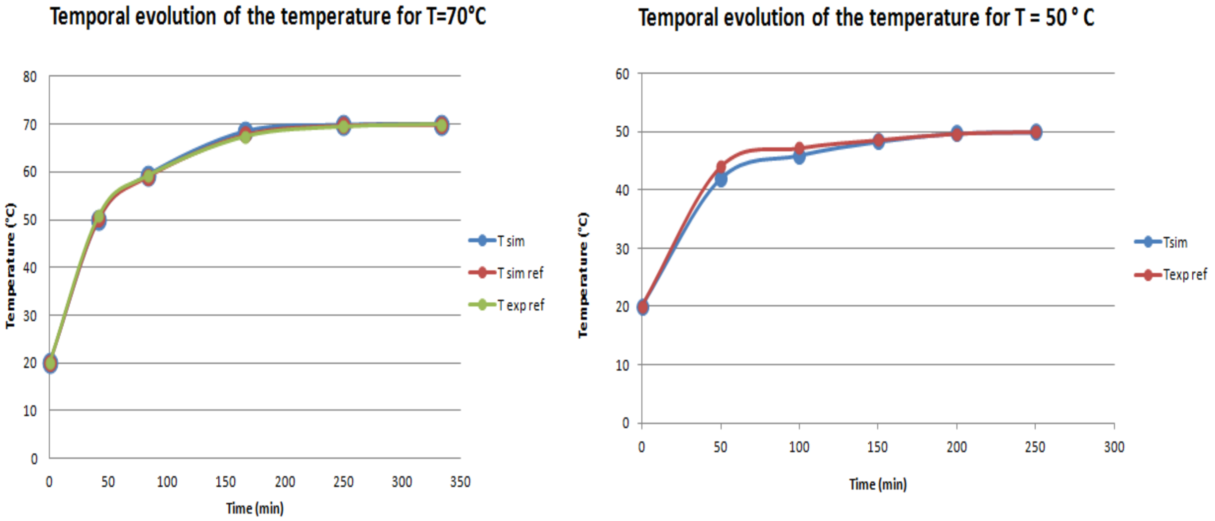


Fig. 3. Comparison of the present results with the predictions and measurements of temperature history under conditions: T = 70 °C, V = 1.5m / s, HR = 20% (left) and for T = 50 °C, V = 1.5m / s, HR = 20% (right).

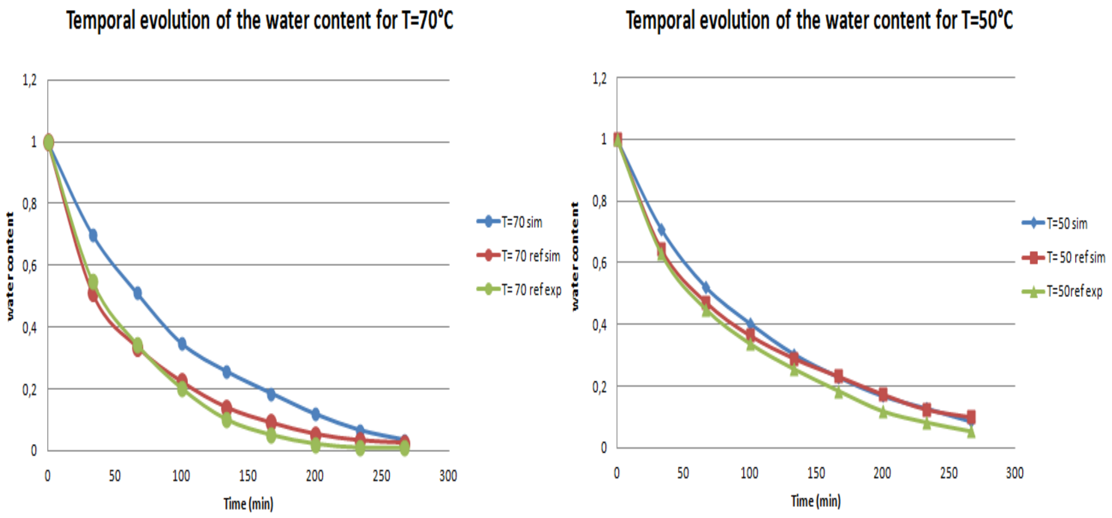
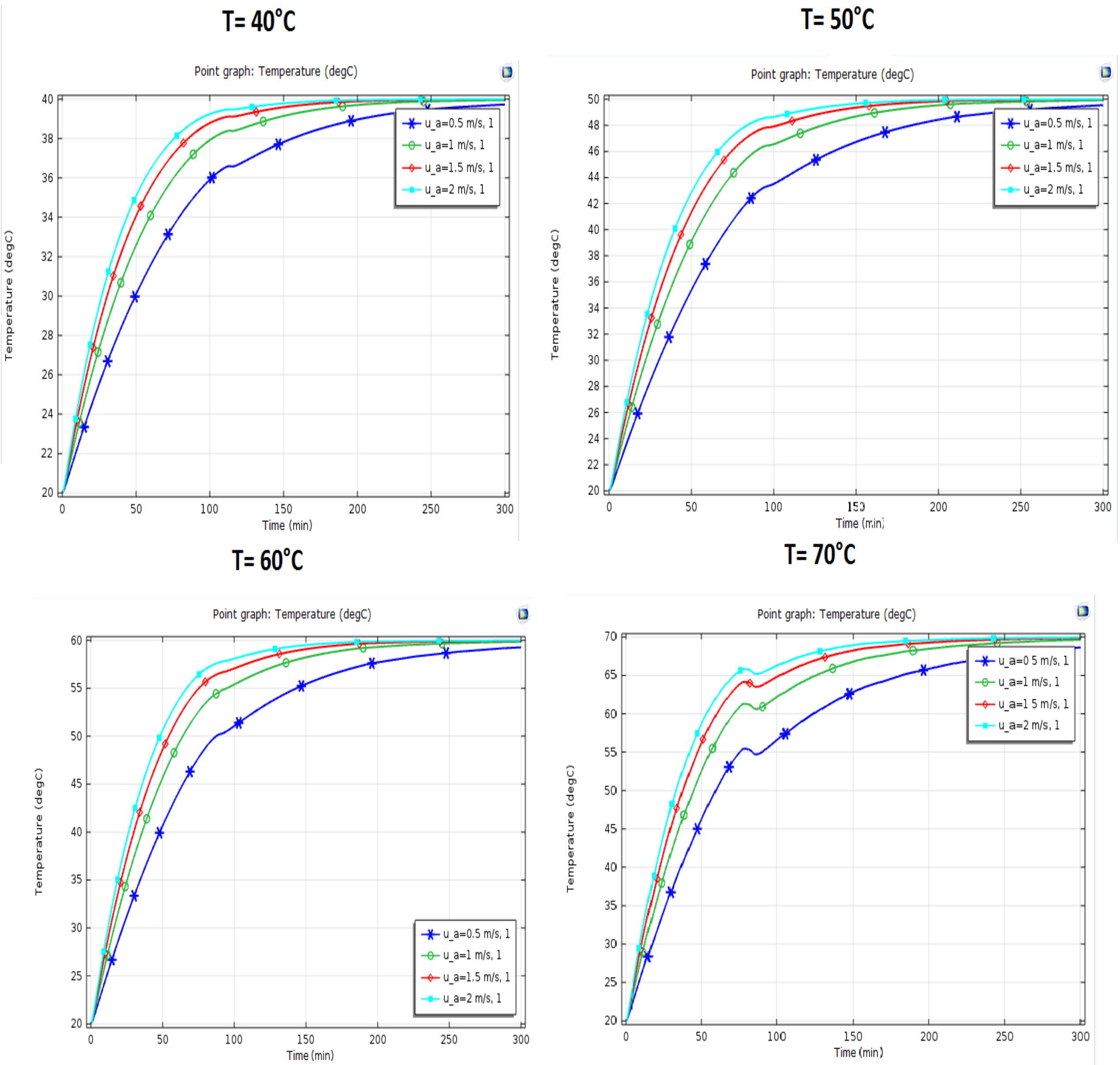


Fig. 4. Comparison of the present results with the predictions and measurements for the water content time evolution for T = 70 °C, V = 1.5 m / s and HR = 20% (left) and for T = 50 °C, V = 1.5 m / s and HR = 20% (right).

3.2. Effect of the velocity variation

Figure 5 shows the effect of the variation of the drying air velocity on the drying process for different drying temperatures. Note that when increasing the drying air velocity, keeping fixed other parameters, the drying process becomes faster. Some researchers have found a negligible effect of air velocity on drying kinetics and they explained this by the low value of external resistance to moisture transfer compared to that of internal resistance.



T= 40°C

T= 50°C

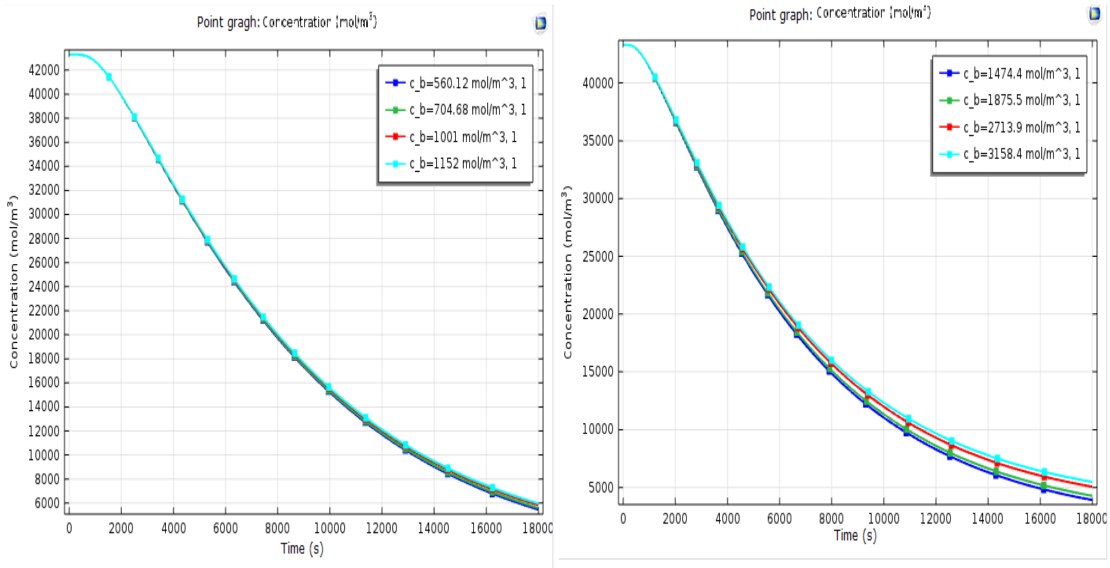
T= 60°C

T= 70°C

Fig. 5. Effect of the drying air velocity on apple sample temperature.

3.3. Effect of the Bulk concentration

Figure 6 shows the effect of Bulk concentration on the moisture concentration at point P1 (see Figure 1) as the influence of relative humidity on water content. It can be seen that the bulk concentration has a small effect on the drying kinetics. This effect becomes weaker as the temperature increases because the evaporation rate is greater than the diffusion rate of the water from the inside to the surface of the apple slice. A slowing down of the drying process is also noted.



T=50°C

T= 70°C

Fig. 6. Effect of Bulk concentration on moisture concentration at control point P1.

3.4. Simulation of the mechanical behavior

3.4.1. Comparison

The majority of the values of the quantities tested for different drying conditions and different calculation times are of the same order of magnitude. The noticed deviations can be attributed to several modeling factors:

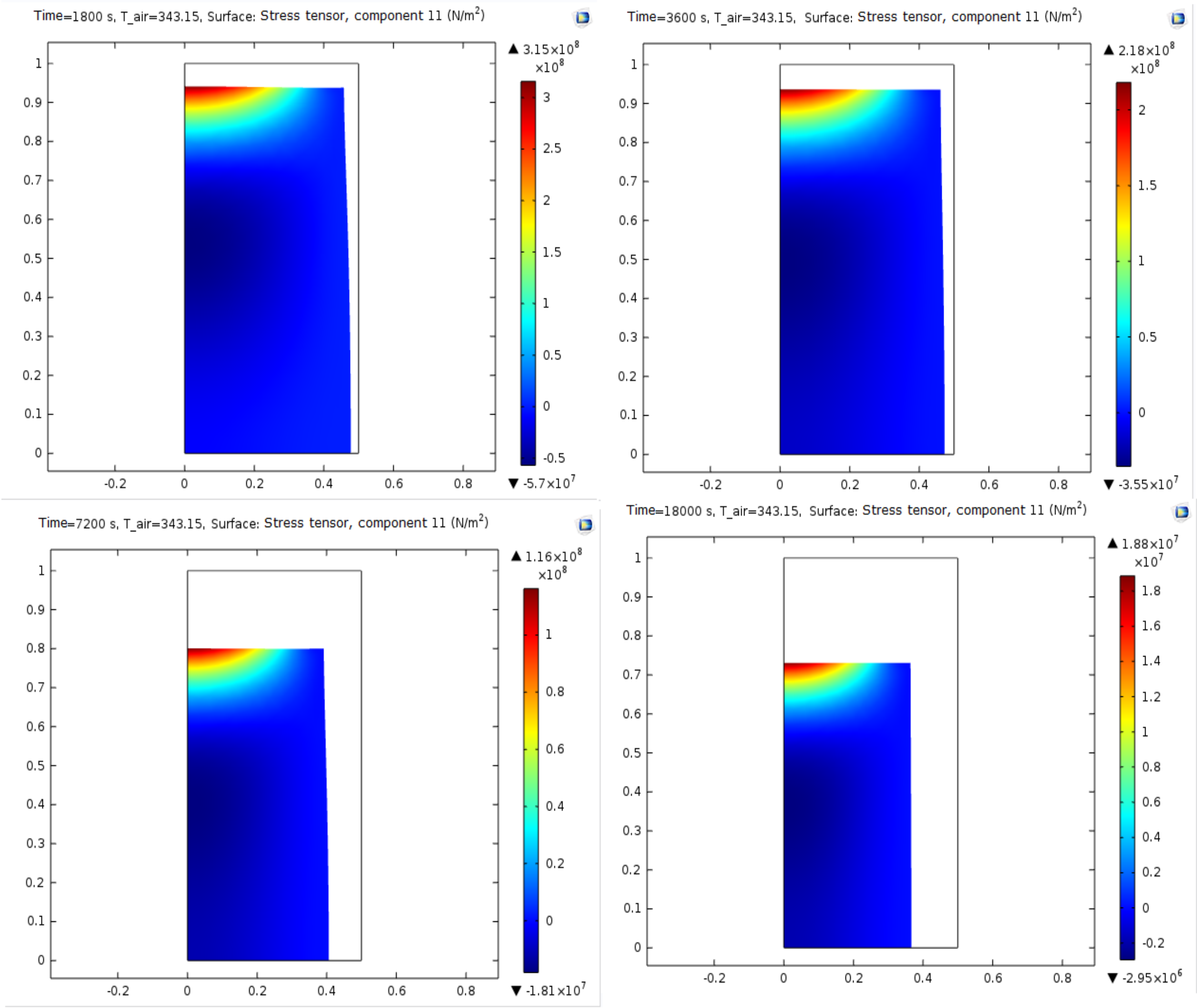
a) Porosity taken here constant mean depending on the temperature for reasons of simplicity and variable catch in the model of Toujani *et al.* [14].
b) The heat transfer coefficient taken here from the software library and taken from the reference as a variable correlation as a function of the drying air velocity,
c) The modeling of the mechanical behavior taken here as anisotropic for reasons of reproduction of the reality whereas it was idealized for the study of the references,
d) The model here is tri-phase whereas it is bi-phasic in the references.

3.4.2. Analysis

The mechanical stress distributions in a half-section of a parallelepiped apple sample for different conditions and at four drying times: half - hour, one hour, two hours and five hours are presented in Figure 7, 8 and 9. The contraction of the sample generates a negative shear stress in the sample with a maximum value in the corners, which causes the degradation of its right corners. Also, the figures indicate the size and shape of the actual sample of the process.

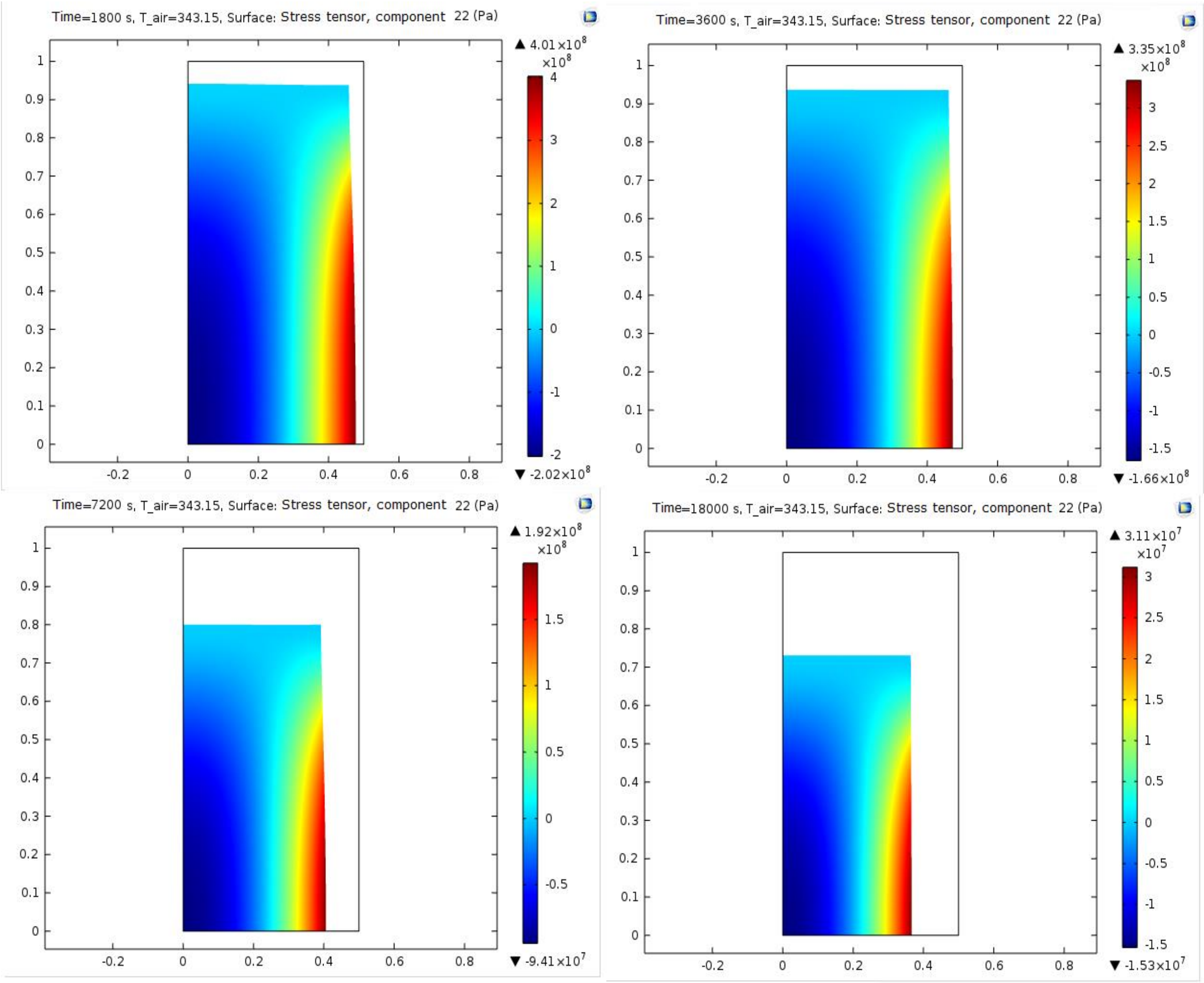
The present results are consistent with the results obtained by Toujani et al. apart from the deformation which is quasi-linear after a certain amount of time. The same way takes place when the principal compressive stress is the maximum. This corresponds to the impact of the temperature of drying on product shrinkage and maximum moisture gradients.

In the above part the hydro-thermo-viscoelastic modeling of the convective drying of a highly deformable product saturated with water is studied using the COMSOL Multiphysics commercial software. Our model was validated on the basis of literature and the influence of a set of parameters on the kinetics of drying and the mechanical behavior is investigated. Subsequently, an optimization of these parameters, in the following part, by the help of fractional experiment plans technique will be considered in order to obtain the best operating conditions of the drying kinetics.



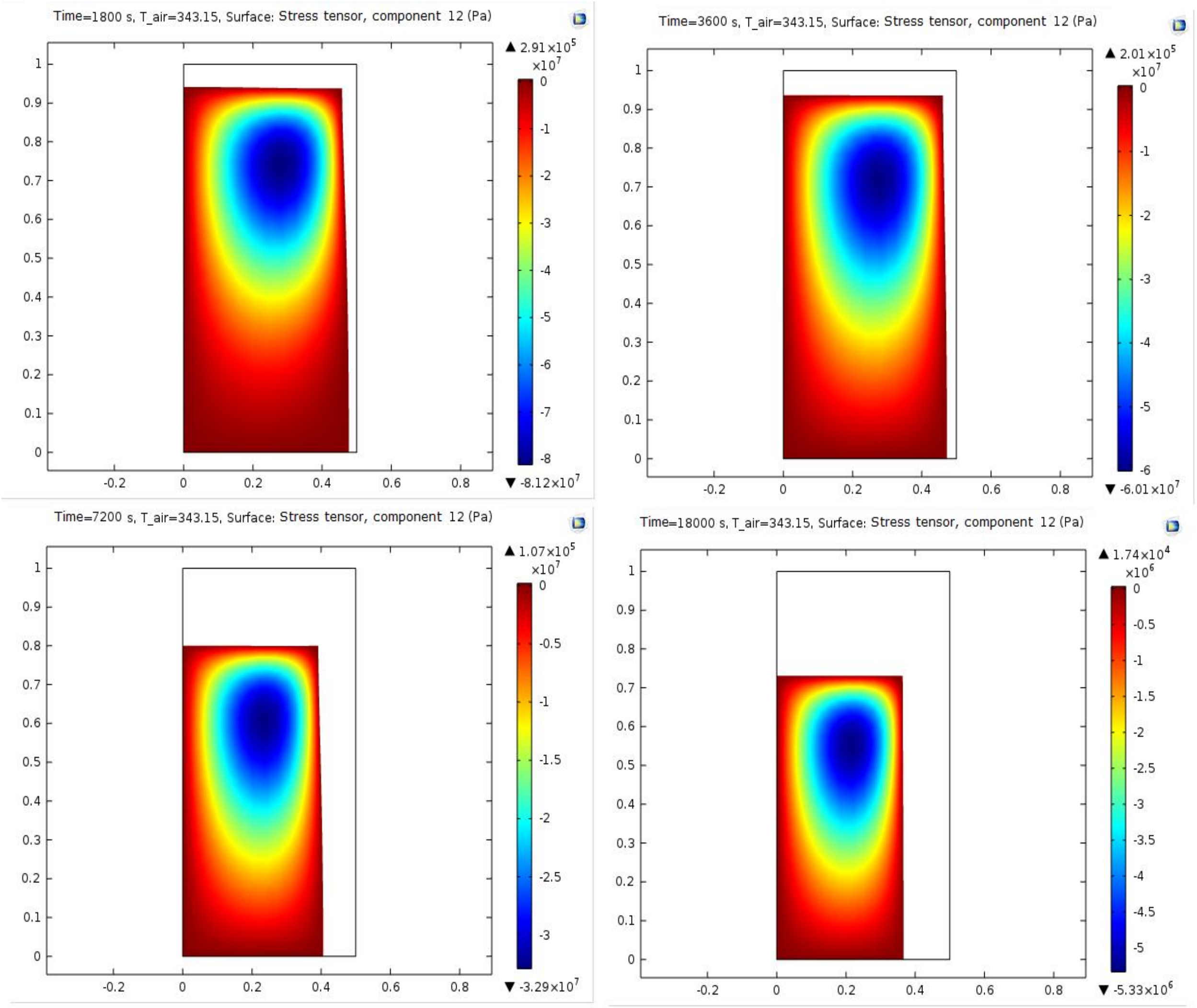
Stress tensor component xx, T= 70°C

Fig. 7. Distribution of mechanical stresses component $\boldsymbol{\sigma}_{\mathbf{xx}}$ at T = 70 °C, V = 1.5m / s and HR = 20%.



Stress tensor componentyy , T= 70°C

Fig. 8. Distribution of mechanical stresses component $\boldsymbol{\sigma_{yy}}$ at T = 70 °C, V = 1.5m / s and HR = 20%.



Stress tensor component xy, T= 70°C

Fig. 9. Distribution of mechanical stresses component: $\boldsymbol{\sigma}_{\mathbf{xy}}$ at T = 70 °C, V = 1.5m / s and HR = 20%.

4. Conclusions

The aim of this study is to conduct a hydro-thermo-viscoelastic modelling of the convective drying of a highly deformable product saturated with water using the COMSOL Multiphysics commercial software.

Our model is validated on the basis of literature and the influence of a set of parameters on the kinetics of drying and the mechanical behaviour is investigated. The study is a multi-inlet-parameters: parameters related to drying air (velocity, moisture content), parameters related to drying atmosphere (air temperature, pressure). The hygrothermal model permitted an expanded evaluation of the drying process. Such modelling for redistribution of kinetic humidity can be helpful to improve and optimize the intermittent drying processes, among others. Afterwards, an optimization of these parameters by means of fractional experiment plans technique will be considered in order to obtain the best operating conditions of the drying kinetics.

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