A Multiphase Model to Analyze Transport Phenomena in Convective Drying

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Abstract: The aim of the present work was the formulation of a theoretical model describing the transport phenomena involved in food drying process. The simultaneous transfer of momentum, heat and water, both as liquid and as vapor, were described accounting for the variation of food sample volume. The volume variation, generally neglected by the available theoretical models but actually occurring during real processes, was calculated by a proper structural mechanics analysis that allowed determining the anisotropic displacements (shrinkage) of food due to water evaporation. These displacements, described by the Arbitrary Lagrangian Eulerian (ALE) method, determined a modification of both the integration domains (air and food), accounted for by the present model.
Keywords: Food, Finite Elements Method, Shrinkage

List of symbols

[A]	Matrix defined by eq. 19	1/m
C^+	Universal constant for smooth walls	-
C_2	Water concentration in air	mol/m^3
C_{pa}	Air specific heat	J/(kg K)
C_{ps}	Food specific heat	J/(kg K)
C_v	Vapor concentration in food	mol/m^3
C_w	Liquid water concentration in food	mol/m^3
dU	Total displacement	m
$d\varepsilon$	Total strain	-
$d\varepsilon_o$	Shrinkage strain	-
$d\varepsilon_s$	Mechanical strain	-
$d\sigma$	Mechanical stess	Pa
[D]	Stress-strain matrix	Pa
D_a	Diffusion coefficient of water in air	m^2/s
D_v	Effective diffusion coefficient of vapor in food	m^2/s
D_w	Capillary diffusion coefficient of water in food	m^2/s
$\underline{I}$	Identity matrix	-
$\dot{I}$	Volumetric rate of evaporation	mol/(m^3 s)
k	Turbulent kinetic energy	m^2/s^2
k_a	Air thermal conductivity	W/(m K)
k_{eff}	Effective thermal conductivity of food	W/(m K)
$\underline{n}$	Unity vector normal to the surface	-
p	Pressure within the drying chamber	Pa
p_v	Vapor pressure of water	Pa
p_{vs}	Saturated vapor pressure of water	Pa
R	Gas constant	J/(mol K)
r	Spatial coordinate	m
T	Food temperature	K
t	Time	s
T_2	Air temperature	K
T_{air}	Air temperature at the drier inlet	K
$\underline{u}$	Averaged velocity field	m/s
$\underline{u}'$	Fluctuating part of velocity field	m/s
u_0	Air velocity at the drier inlet	m/s
u_τ	Friction velocity	m/s
U_r	Relative humidity of air	-
V	Food volume	m^3
<Xb>	Average moisture content-dry basis	kg $_w$/kg$_{ds}$
X_b	Moisture content on a dry basis	kg $_w$/kg$_{ds}$
z	Spatial coordinate	m

Greek Symbols

α	Constant comparing in k-ω model	-
β	Constant comparing in k-ω model	-
β_k	Constant comparing in k-ω model	-
δ_w	Distance from the wall	m
κ	von Karman's constant	-
η_a	Air viscosity	Pa s
η_t	Air turbulent viscosity	Pa s

λ	Water latent heat of vaporization	J/mol
ρ_a	Air density	kg/m^3
ρ_s	Food Density	kg/m^3
σ_k	Constant comparing in k-ω model	-
σ_ω	Constant comparing in k-ω model	-
ω	Dissipation per unit of turbulent kinetic energy	

subscripts

0	Initial condition (*t*=0)
atm	Atmospheric conditions
ds	On dry basis (dry solid)
r	Spatial coordinate
w	On wet basis
z	Spatial coordinate

superscripts

T	Transpose

1. Introduction

Water removal from hygroscopic materials (like foods) is a rather complex phenomenon, since both unbound and bound water are actually to be transported. Generally, bound water is removed by progressive vaporization within the solid matrix, followed by diffusion and pressure driven transport of water vapor through the solid [Mayor and Sereno 2004]. During drying, due to the porosity of food matter, water evaporation takes place inside the food as well as at the food external surface. An exhaustive analysis of all the complex transport phenomena involved in the drying process was regarded as being too onerous and time consuming for practical purposes [Ratti 1994]. The simultaneous presence of both liquid water and vapor within the solid makes drying modeling even more difficult [Chen 2007]. The transport phenomena occurring at the food-air interfaces were often described in terms of heat and mass transfer coefficients, estimated from the available literature data. This practice, however, limited the model accuracy since even small errors in the estimation of the transfer coefficients could lead to large deviations between predicted and real values, thus determining inappropriate equipment design or severe processing problems [Kondjoyan and Boisson 1997; Verboven, Nicolaï et al. 1997]. Moreover, the estimation of interfacial transport rates by heat/mass transport coefficients is actually unreliable when food shape is not regular or it even changes with time, due to shrinkage [Mayor and Sereno 2004; Ratti 1994]. As drying proceeds, in fact, the initial mechanical equilibrium, which determines the food size and its shape, fails due to the water transport from the solid matrix; progressive modification of the food structure is, therefore, observed. The rapid removal of water during drying does not allow the attainment of a new equilibrium state within the solid matrix, whose main characteristics (mechanical properties, porosity, shape, dimension, etc.) are not constant and vary with time. On the basis of the previous discussion, it is evident that a proper modeling of shrinkage cannot leave a structural analysis of food sample out of consideration. A proper characterization of food sample deformations, however, is strongly dependent on the actual heat and water rates, which, in turn, are affected by the velocity field of drying air flowing around the food sample.

The aim of the present work was the formulation of a multiphase transport model aimed at the exhaustive description of convective drying process. The model was based on the conservation of liquid water, vapor and energy, both in air and in food domain. The turbulent momentum transfer of drying air, considered as a gas mixture owing to its relative humidity always different from zero, was also considered and described by the k-ω model [Wilcox, 2004], which – as compared to the simpler k-ε model – allowed improving the model predictions, especially in the boundary layer developing close to the food surfaces. To properly describe the shrinkage, the classical transport equations were coupled with a structural mechanics analysis performed on the food sample, i.e. a cylindrical shaped potato whose mechanical properties, depending on the local value of food moisture content, were taken from the literature [Yang and Sakai, 2001]. The calculated displacements of food sample were necessary to estimate, by an ALE method, the actual deformation of the mesh and, therefore, the variations of both the integration domains (food and air) involved in the present process modeling.

The system of non-linear unsteady-state partial differential equations resulting from the formulation of the present model were solved by the Finite Elements Method implemented by Comsol Multiphysics® 3.4.

2. Theory

The food under study was a cylindrical potato sample dried in a convective oven. It was assumed that drying air was continuously supplied to the oven inlet section and flowed around the food sample in the axial direction, parallel to its length (Fig. 1). The portion of drier under investigation had a length of 0.15 m and a radius of 0.08 m. The food sample, assumed to be a cylinder 0.05 m long and 6 10^{-3} m radius, was placed 0.04 m far from the drier inlet.

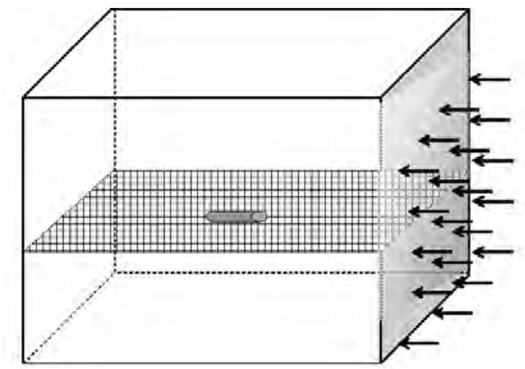

Figure 1. Schematic representation of the drying chamber.

The present theoretical model actually represented an improvement of a previous study [Curcio, 2010]. The following main assumptions were formulated: a) heat and mass transfer resistance were assumed negligible across the mesh on which food was placed [Thorvaldsson and Janestad 1999; Viollaz and Rovedo 2002]. The system under investigation was symmetric and only half of the original domain was considered. Moreover, the variation occurring in the θ direction (i.e. the angular coordinate) was neglected, thus restricting the analysis to a 2D geometry. Each dependent variable was, therefore, function of the radial and axial coordinates, *r* and *z*, respectively, and of time, *t*. b) All the phases, i.e. solid, liquid, and gas, were continuous. c) All the phases were in local thermal equilibrium. d) Vapor pressure was a function of both temperature and moisture content. e) The transport of liquid water was due to both gas pressure and capillary pressure gradients; capillary pressure, however, prevailed over gas pressure assuming that the hygroscopic material under study was highly unsaturated, like in most drying applications. The transport of liquid water, therefore, occurred essentially by capillary pressure. f) Vapor was transferred by pressure and concentration gradients; the term containing pressure driven flow, however, was neglected and molecular diffusion was considered as the prevailing mechanism. It is worthwhile remarking that the previous assumptions e) and f) may describe well, for instance, lower temperature drying processes, for which pressure driven flow is not as important [Datta, 2007]. g) In the food sample, the contribution of convection to heat transport was considered negligible as compared to conduction (Peclèt number in radial direction tending to nil) and, therefore, was ignored; the conservation equation referred to air transport in the food sample was neglected, too. h) The food sample was a multiphase hygroscopic porous medium; yet, it was assumed to be a fictitious continuum. i) Evaporation occurred over the entire food domain and also at food outer surfaces. j) Moisture removal from the surface took place by vapor transport, diffusing into the boundary layer developing in the drying air, and by liquid water transport, evaporating at the outer food surfaces. Both vapor and liquid water were convected away by the drying air, whose velocity field is expected to affect strongly the interfacial rates of heat and mass transfer as it was found, for instance, in the case of tangential flow along immersed bodies with simultaneous heat and mass transfer into the fluid stream [Bird et al. 2002]. k) The continuity of both heat and mass fluxes occurred at the food/air interfaces.

On the basis of the above assumptions, the unsteady-state mass balance equations referred to the transport of liquid water and vapor in the food sample led, respectively, to [Bird et al. 2002, Zhang and Datta, 2004]

$$\partial C_w / \partial t + \underline{\nabla} \cdot \left(- D_w \underline{\nabla} C_w \right) + \dot{I} = 0 \qquad (1)$$

$$\partial C_v / \partial t + \underline{\nabla} \cdot \left(- D_v \underline{\nabla} C_v \right) - \dot{I} = 0 \qquad (2)$$

The energy balance in the food material led, according to the Fourier's law, to the unsteady-state heat transfer equation [Bird et al. 2002, Zhang and Datta, 2004]:

$$\rho_s C_{p_s} \partial T / \partial t - \underline{\nabla} \cdot \left(k_{eff} \underline{\nabla} T \right) + \lambda \cdot \dot{I} = 0 \qquad (3)$$

Obtaining $\dot{I}$ from Eq. 2 and replacing it in Eqs. 1 and 3, the following expressions were derived:

$$\partial C_w / \partial t + \partial C_v / \partial t + \underline{\nabla} \cdot \left(- D_w \underline{\nabla} C_w\right) + \underline{\nabla} \cdot \left(- D_v \underline{\nabla} C_v\right) = 0 \quad (4)$$

$$\rho_s C_{p_s} \partial T / \partial t + \underline{\nabla} \cdot \left(- k_{eff} \underline{\nabla} T\right) - \lambda \cdot \left(- \partial C_w / \partial t + \underline{\nabla} \cdot \left(D_w \cdot \underline{\nabla} C_w\right)\right) = 0 \quad (5)$$

The vapor concentration, *Cv*, was defined using the ideal gas assumption, thus its time-derivative and gradient read as:

$$\partial C_v / \partial t = 1/RT \left[\partial T / \partial t \left(\partial p_v / \partial T - p_v / T \right) + \partial p_v / \partial C_w \cdot \partial C_w / \partial t \right] \quad (6)$$

$$\underline{\nabla} C_v = 1/RT \left[\underline{\nabla} T \cdot \left(\partial p_v / \partial T - p_v / T \right) + \partial p_v / \partial c_w \cdot \underline{\nabla} c_w \right] \quad (7)$$

where *pv* was the vapor pressure of water expressed, through an equilibrium relationship, as a function of local values of both temperature and moisture content [Ratti et al. 1987]:

$$\ln \frac{p_v}{p_{vs}(T)} = - 0.0267 X_b^{-1.656} + 0.0107 \exp(-1.287 X_b) X_b^{1.513} \ln(p_{vs}(T))$$
(8)

It is worthwhile remarking that the physical and the transport properties of food, as introduced in the above system of PDEs, were expressed in terms of the local values of temperature and of moisture content, as suggested by the available literature relationships.

As far as drying air was concerned, the unsteady-state momentum balance, i.e. the so-called Reynolds-averaged Navier-Stokes equations, coupled to both the continuity equation and the transport equations for k and ω led to [Wilkox 2004]:

$$\partial \rho_a / \partial t + \underline{\nabla} \cdot \rho_a \underline{u} = 0 \quad (9)$$

$$\rho_a \partial \underline{u} / \partial t + \rho_a \underline{u} \cdot \underline{\nabla} \underline{u} + \underline{\nabla} \cdot \left(\overline{\rho_a \underline{u}' \otimes \underline{u}'} \right) = - \underline{\nabla} p + \underline{\nabla} \cdot \left[\eta_a \left(\underline{\nabla} \underline{u} + (\underline{\nabla} \underline{u})^T \right) \right] \quad (10)$$

$$\rho_a \partial k / \partial t + \rho_a \underline{u} \cdot \underline{\nabla} k = \underline{\nabla} \cdot [(\eta_a + \sigma_k \eta_t)(\underline{\nabla} k)] + \frac{\eta_t}{2} \left(\underline{\nabla} \underline{u} + (\underline{\nabla} \underline{u})^T \right)^2 - \beta_k \rho_a k \omega$$
(11)

$$\rho_a \partial \omega / \partial t + \rho_a \underline{u} \cdot \underline{\nabla} \omega = \underline{\nabla} \cdot [(\eta_a + \sigma_\omega \eta_t)(\underline{\nabla} \omega)] + (\alpha \omega / 2k) \eta_t \left(\underline{\nabla} \underline{u} + (\underline{\nabla} \underline{u})^T \right)^2 - \beta \rho_a \omega^2$$
(12)

The deviating part of the Reynolds stress was expressed as:

$$\rho_a \left(\overline{\underline{u}' \otimes \underline{u}'} \right) - \rho_a / 3 \; trace \left(\overline{\underline{u}' \otimes \underline{u}'} \right) \underline{I} = - \left[\eta_t \left(\underline{\nabla} \underline{u} + (\underline{\nabla} \underline{u})^T \right) \right] \quad (13)$$

η_t, i.e. the turbulent or eddy viscosity, was defined as:

$$\eta_t = \rho_a k / \omega \quad (14)$$

and the spherical part, introduced in Eq. 13, was written in terms of the turbulent kinetic energy, in order to attain a proper *closure* for the turbulence model:

$$\rho_a / 3 \; trace \left(\overline{\underline{u}' \otimes \underline{u}'} \right) \underline{I} = 2/3 \; \rho_a k \quad (15)$$

The energy balance in the drying air, led to [Bird et al. 2002]:

$$\rho_a C_{pa} \partial T_2 / \partial t - \underline{\nabla} \cdot \left(k_a \underline{\nabla} T_2 \right) + \rho_a C_{pa} \underline{u} \cdot \underline{\nabla} T_2 = 0 \quad (16)$$

Finally, the mass balance on water, as vapor, in the drying air, led to [Bird et al. 2002]:

$$\partial C_2 / \partial t + \underline{\nabla} \cdot \left(- D_a \underline{\nabla} C_2 \right) + \underline{u} \cdot \underline{\nabla} C_2 = 0 \quad (17)$$

Eqs. 4-5 9-12 and 16-17 represented a system of unsteady, non-linear, partial differential equations. A set of initial conditions, typically prevailing in an industrial drying process, was necessary to perform the numerical simulations. As far as air was concerned, it was assumed that the temperature in the drying chamber, T_{20}, had the value of 298 K and that the water concentration, C_{20}, was equal to 0.642 mol/m^3 (corresponding to a relative humidity, U_{r0}, of 50%). It was also assumed that, before the drying process occurred, the air was stationary and that the pressure in the drying chamber, p_0, was 1 atm. The initial values of food temperature, T_0, and of its moisture content, C_0, were set equal to 283 K and to 48046 mol/m^3, respectively. The adopted C_0 value referred to an average initial moisture content typical of fresh potatoes and corresponding to 0.8 kg H_2O/kg$_w$ (on wet basis) or to 4.06 kg H_2O/kg$_{ds}$ (on dry basis). The boundary conditions were summarized in Fig. 2 where each different boundary was identified by an integer ranging from 1 to 9.

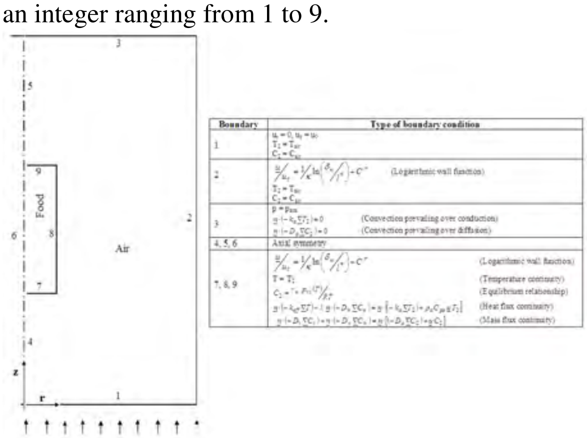

Figure 2. Boundary conditions used to formulate the theoretical model.

At the food-air interface, where no accumulation occurred, the continuity of heat and water fluxes, both as liquid and vapor, was imposed. Moreover, a thermodynamic equilibrium at the air-food interface was formulated and expressed in terms of water activity (eq. 8), thus accounting also for the effects of physically bound water. On boundary 2, it was assumed that air temperature and its moisture concentration were equal to the values measured at the drier inlet. These two conditions are actually valid under the assumption that the temperature and concentration profiles were confined to two very thin regions which developed close to the food-air interface. At the drier outlet (boundary 3), conduction and diffusion were neglected in favour of convection, which prevailed. Finally, the boundary conditions for momentum balance at the solid surfaces were expressed in terms of a logarithmic wall function.

Food shrinkage was modeled defining the local total strains {dε} as a function of changes in mechanical strains {$d\varepsilon_s$} (constrained deformation due to food mechanical properties) and in shrinkage strains {$d\varepsilon_0$}:

$$\{d\varepsilon\}=\{d\varepsilon_s\}+\{d\varepsilon_0\} \tag{18}$$

Total strain {dε} was actually a function of the total displacement {dU}

$$\{d\varepsilon\}=[A]\{dU\} \tag{19}$$

The changes in stresses {dσ} were function of the variations of mechanical strains {$d\varepsilon_s$}

$$\{d\sigma\}=[D]\{d\varepsilon_s\} \tag{20}$$

To express the free drying shrinkage strains {$d\varepsilon_0$}, it was assumed that the free deformation due to moisture loss was proportional to the time variation of water content, through a constant (the hydrous compressibility factor) [Benboudjema, 2005]. This constant was preliminarily estimated from the experimental data showing drying shrinkage vs. weight loss. The virtual work principle was formulated to determine the equilibrium equation. Assuming that zero body and surface forces were applied to the food sample, it was obtained that:

$$\int_V \delta\{d\varepsilon\}^T\{d\sigma\}dV=0 \tag{21}$$

As far as the boundary conditions were concerned, one side of the food rested on the drier net and was characterized by a null displacement in z direction, whereas the other exposed food surfaces were free to move. The calculated displacements were used to determine the actual modifications of integration domains and, therefore, to solve the present moving boundary problem represented by the anisotropic and progressive reduction of food sample volume.

3. Use of COMSOL Multiphysics

The solution of the present model was performed by Comsol Multiphysics 3.4 and actually consisted of the following sequential steps: 1) the coupled transfer of momentum (for air only) of heat and of water (for both food and air), together with the virtual work principle, was initially solved with reference to fixed domains; 2) the obtained solutions, in particular, the actual displacements occurring in the food sample as a consequence of water removal and depending on food mechanical properties were, then, used as inputs to calculate the mesh deformation, according to an ALE description; 3) the complete transport model was solved once again with reference to the deformed domains so as to calculate the actual time evolutions of food volume variation, together with the profiles of all the dependent variables (temperature, moisture content, velocity field, etc.) having a physical significance. The motion of the deformed mesh was modeled using a Winslow smoothing.

Both the domains were discretized by triangular grids, which resulted into a total number of 10802 triangular finite elements, leading to about 130000 degrees of freedom. The mesh was thicker close to the boundaries actually exposed to the drying air and consisted of 5449 elements and 5353 elements within food and air domains, respectively. The considered mesh provided a satisfactory spatial resolution for the system under study; the solution was indeed independent on the grid size, even with further refinements. Lagrange finite elements of order two were chosen for the components, u_r and u_z, of drying air velocity vector $\boldsymbol{u}$, for the turbulent kinetic energy, the dissipation for unit of turbulent kinetic energy, for the pressure distribution within the drying chamber and for the displacements occurring in food sample. As regards water concentration and temperature, for both air and food, , Lagrange finite elements of order three were chosen. The relative and absolute tolerances were set to 0.00001 and 0.000001, respectively.

On a quad-core computer running under Windows Vista 64 bit, a drying time of 4 hours was typically simulated in about 40 minutes when the system of PDEs was referred to a fixed mesh, a much longer time of about 6 hours was instead necessary to achieve the solution in the case of a deformed mesh.

4. Results and Discussion

The proposed model provided helpful indications that were used to calculate the moisture and the temperature distributions within both food and air and to analyze the effect of the operating conditions on drying behavior. For the sake of brevity only some of the most representative results were hereafter presented. Fig. 3 showed the time evolution of potato moisture content (on a dry basis) referred to a domain whose shape and dimension changed with time as a consequence of shrinkage.

It could be observed that, as expected, external surfaces got dry more rapidly than the inner regions.

When, initially, food moisture content was high and, consequently, capillary diffusivity had large values, the moisture exhibited a slight difference between the core and the outer surface. These differences tended progressively to enlarge due to both a decrease in capillary diffusivity and an increase of surface temperature that started rising above the wet bulb temperature (data not shown). During the falling rate period, the evaporation rate prevailed over the capillary flux inside the food; the amount of vapor in the internal holes was significant and the molecular diffusion of vapor took place to a significant extent. Moreover, as shown in Fig. 3, food domain had not an isotropic deformation; in fact, on those sides (where drying air actually impinged) characterized by a higher drying rate, a much larger (and faster) deformation was observed.

The importance of considering food shrinkage so as to attain an improved prediction of the actual values of interfacial heat and water fluxes was confirmed by Fig. 4, showing air velocity profiles as a function of process time. It is worthwhile remarking that the present transport model did not rely on the exploitation of any semi-empirical correlations to calculate the heat and mass transfers at the food/air interfaces; rather, the actual transport rates strongly depended of the air velocity field that, therefore, had to be exactly calculated, time by time, accounting for the variations of food shape and of its dimension.

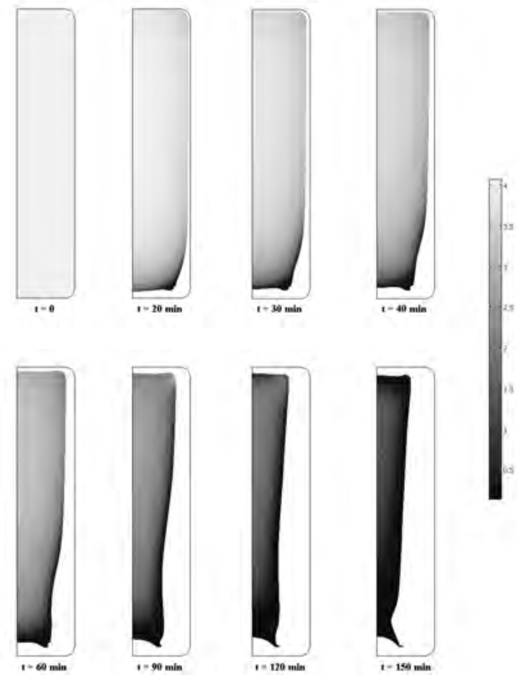

Figure 3. Time evolution of potato moisture content during drying accounting for shrinkage effect (T_{air} = 323 K, U_r = 50%, u_0 = 2.2 m/s).

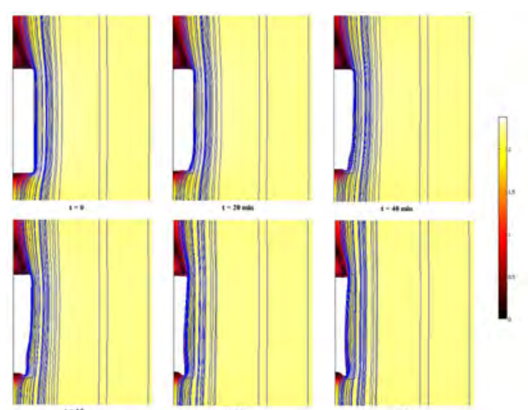

Figure 4. Time evolution of air velocity field and of the streamlines calculated accounting for food shrinkage (T_{air} = 323 K, U_r = 50%, u_0 = 2.2 m/s).

Fig. 5 showed, in a typical case, a comparison between the average moisture content, <Xb>, calculated, respectively with reference to a constant and a variable volume of potato sample. It could be observed that, by the proposed approach, a significant difference of <Xb> occurred throughout the considered time horizon. The predicted time-evolution of food volume exhibited a plateau value after about 140 min.

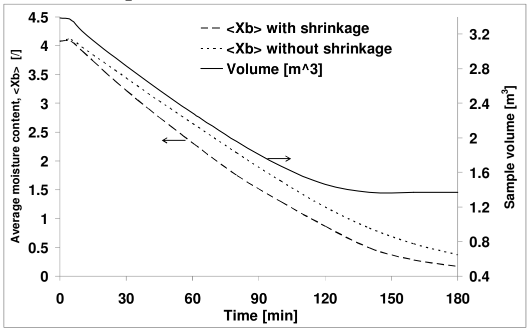

Figure 5. Comparison between the predicted time evolutions of average moisture content (on a dry basis) and food volume variation during drying (T_{air} = 323 K, U_r = 50%, u_0 = 2.2 m/s).

7. Conclusions

The transport phenomena involved in food drying process were analyzed. A general predictive model, i.e. not based on any semi-empirical correlation for estimating heat and mass fluxes at food-air interface, was formulated. The model allowed predicting food shrinkage by coupling the classical transport equations to the virtual work principle, written with reference to a deformed mesh whose movement was described by the ALE method. The obtained results confirmed that, even if much more complicated and time consuming, it is crucial to develop a complete model capable of predicting the actual variation of food shape and to have an insight into the calculation of the mechanical stresses occurring in the sample during drying. This information, in fact, allowed calculating the actual deformation and might also be used as a quality index for dried foods.

8. References

Bird, R.B., Stewart, W.E., Lightfoot, E.N. *Transport Phenomena*, 2nd ed., John Wiley & Sons, London (2002).

Benboudjema F., Meftah F., Torrenti J.M., Interaction between drying, shrinkage, creep and cracking phenomena in concrete, *Engineering Structures*, **27**, 239–250 (2005)

Curcio, S., A Multiphase Model to Analyze Transport Phenomena in Food Drying Processes, *Drying Technology*, **28** (6), 773–785 (2010).

Chen, X. D., Moisture Diffusivity in Food and Biological Materials, *Drying Technology*, **25**, 1203–1213(2007).

Datta, A. K. Porous media approaches to studying simultaneous heat and mass transfer in food processes. I: Problem formulations. *J. Food Eng.*, **80**, 80-95 (2007).

Kondjoyan, A., Boisson, H.C., Comparison of Calculated and Experimental Heat transfer Coefficients at the Surface of Circular Cylinders Placed in a Turbulent Cross-flow of Air, *J. Food Eng.,* **34**, 123-143 (1997).

Mayor, L., Sereno A. M., Modelling shrinkage during convective drying of food materials: a review, *J. Food Eng.*, **61** (3), 373-386, (2004).

Ratti C., Shrinkage During Drying of Foodstuffs, *J. Food Eng.*, **23**, 91-105 (1994).

Ratti, C., Crapiste, G. H., Rotstein, E., A new water sorption equilibrium expression for solid foods based on thermodynamic considerations, *J. of Food Science*, **54**(3), 738–747(1987).

Thorvaldsson, K., Janestad, H., A model for simultaneous heat, water and vapour diffusion, Journal of Food Engineering, **40**, 167-172(1999).

Wilcox, D.C., *Turbulence Modeling for CFD*, 2nd Ed, DCW Industries Inc., (2004).

Verboven, P., Nicolaï, B. M., Scheerlinck, N., De Baerdemaeker, J., The Local Surface Heat Transfer Coefficient in Thermal Food Process Calculations: A CFD Approach, *J. Food Eng.*, **33**, 15-35(1997).

Viollaz, P.E.; Rovedo, C.O. A drying model for three-dimensional shrinking bodies.*J. Food Eng.*, **52**, 149-153(2002).

Yang, H., Sakai, N. and Watanabe, M., Drying model with non-isotropic shrinkage deformation undergoing simultaneous heat and mass transfer, *Drying Technology*, **19** (7), 1441-1460 (2001).

Zhang J., Datta A. K., Some considerations in modeling of moisture transport in heating of hygroscopic materials, *Drying Technology*, **22** (8), 1983-2008 (2004).