A Theoretical Model for the Control of Color Degradation and Microbial Spoilage Occurring in Food Convective Drying

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Introduction: Formulation of a general model given as the combination of the transport model (describing the simultaneous transfer of momentum, heat and mass occurring in a convective drier where hot dry air flows, in turbulent conditions, around a cylindrical potato sample), of the product decontamination model and of the model aimed at predicting the kinetics of color changes occurring during drying.

Aim of the work: Identification, on the basis of a dynamic optimization algorithm, of a set of operating conditions that are to be chosen so as to achieve, at the same time, high-quality and safe dried foods.

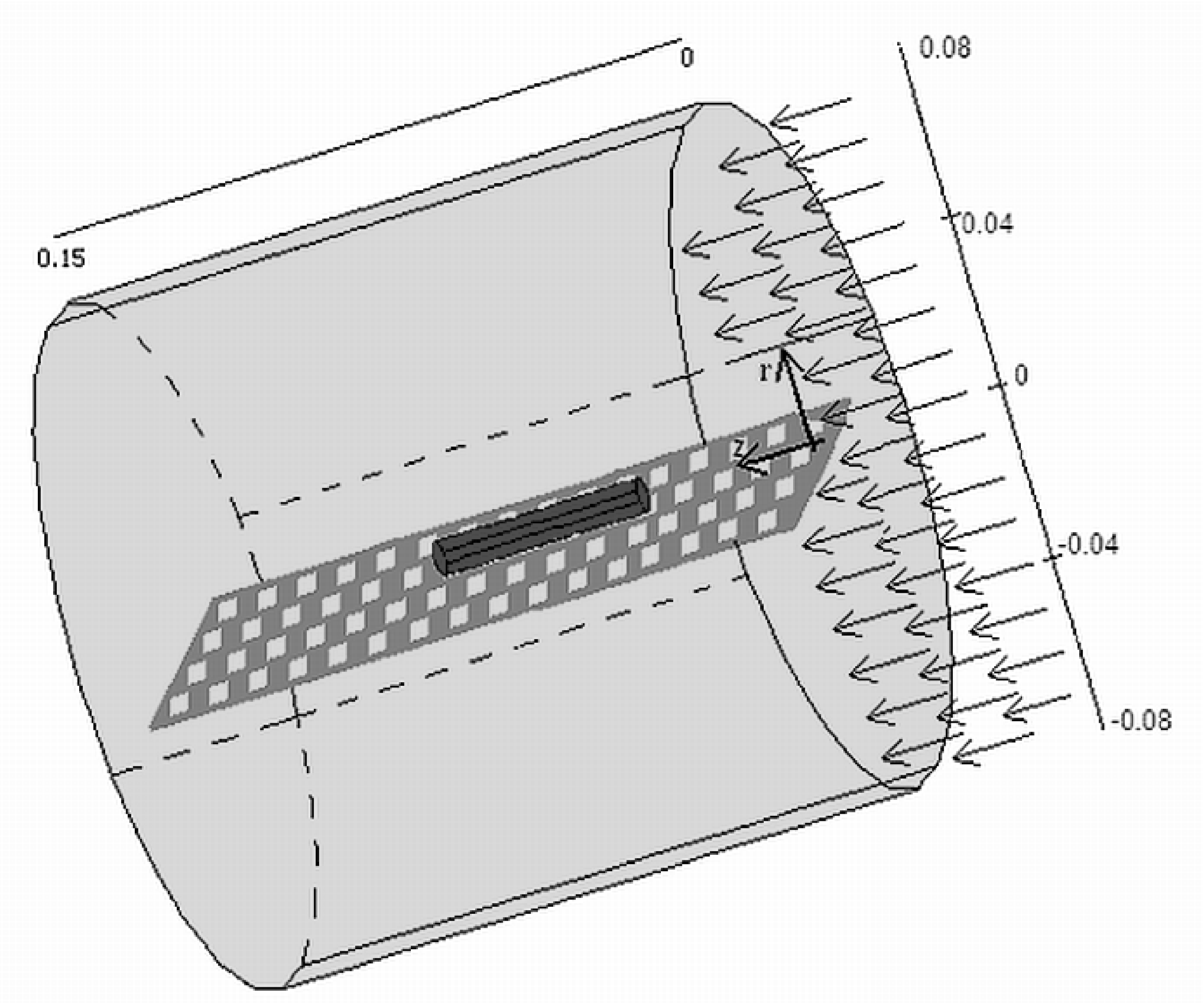

Figure 1. Schematic representation of the drying chamber

Computational Methods: Main hypotheses:

- vapor and liquid water in phase equilibrium at any time
- vapor pressure function of the local values of temperature and moisture content
- evaporation occurred over the entire food domain and also at food outer surfaces
- convective transport negligible
- the conservation equation referred to air transport negligible
- The product decontamination was described considering the microbial inactivation kinetics of Listeria monocytogenes (Valdramidis et al., Journal of Food Engineering, 2006, 76, 79)
- The kinetics of color changes was described in terms of the so called Hunder parameters: C was each of the color parameter (a, b, L), ((Krokida et al., DRYING TECHNOLOGY, 1998, 16(3-5), 667)

Food domain

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

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

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

$$\frac{dN}{dt}=-k_{\max}\cdot\left(\frac{1}{1+Cc}\right)\cdot N$$

$$k_{\max}(T,a_w)=\frac{\ln 10}{1.8}\exp\left(\frac{\ln 10}{7.11}(T-60)\right)\cdot\exp\left(\frac{\ln 10}{0.231}(a_w-1)\right)$$

$$\frac{dCc}{dt}=-k_{\max}\cdot Cc$$

$$\frac{C-C_e}{C_0-C_e}=\exp(-k_c t)$$

$$Ce=C_{e0}(T_a/70)^{a_T}(H/30)^{a_H}$$

$$k_c=K_{c0}(T_a/70)^{m_T}(H/30)^{m_H}$$

Air domain

$$\partial C_2 \Big/ \partial t + \underline{\nabla}\cdot\left(-D_a\underline{\nabla}C_2\right)+\underline{u}\cdot\underline{\nabla}C_2=0 \quad \rho_a C_{pa}\,\partial T_2 \Big/ \partial t - \underline{\nabla}\cdot\left(k_a\underline{\nabla}T_2\right)+\rho_a C_{pa}\underline{u}\cdot\underline{\nabla}T_2=0$$

$$\partial\rho_a \Big/ \partial t + \underline{\nabla}\cdot\rho_a\underline{u}=0$$

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

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

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

No heat/mass transfer coefficient is needed; the proposed approach is useful when food shape changes irregularly with time (shrinkage)

System of non-linear PDEs solved by FEM (Comsol Multiphysics).Total number of 16842 triangular finite elements leading to about 142000 DOFs. The mesh consisted of 8505 and 7977 elements for food and air domains, respectively (Fig. 2). The considered mesh provided a good spatial resolution and the solution was independent on the grid size even with further refinements. Lagrange finite elements of order two were chosen for all the variables.

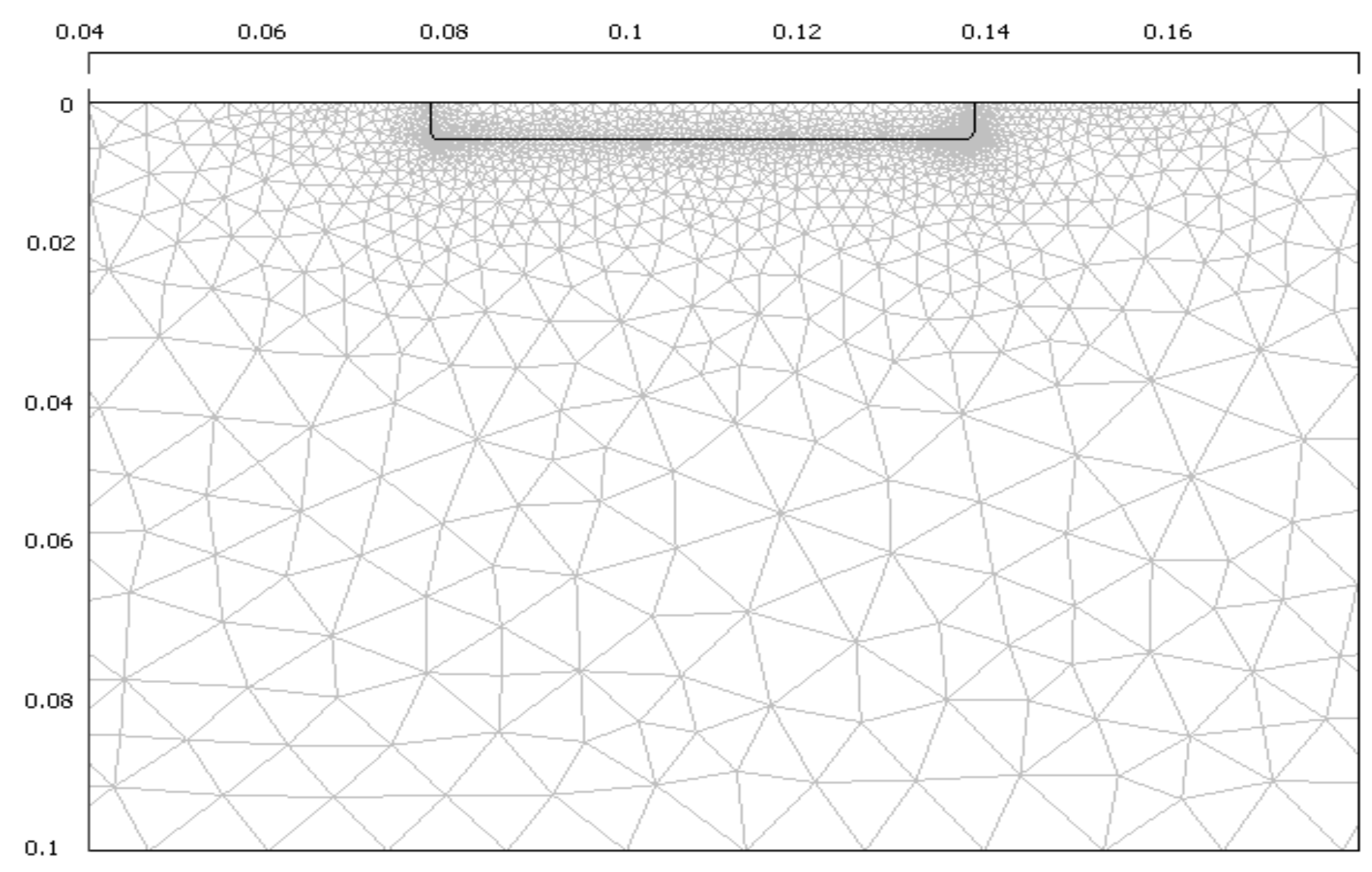

Figure 2. mesh mode

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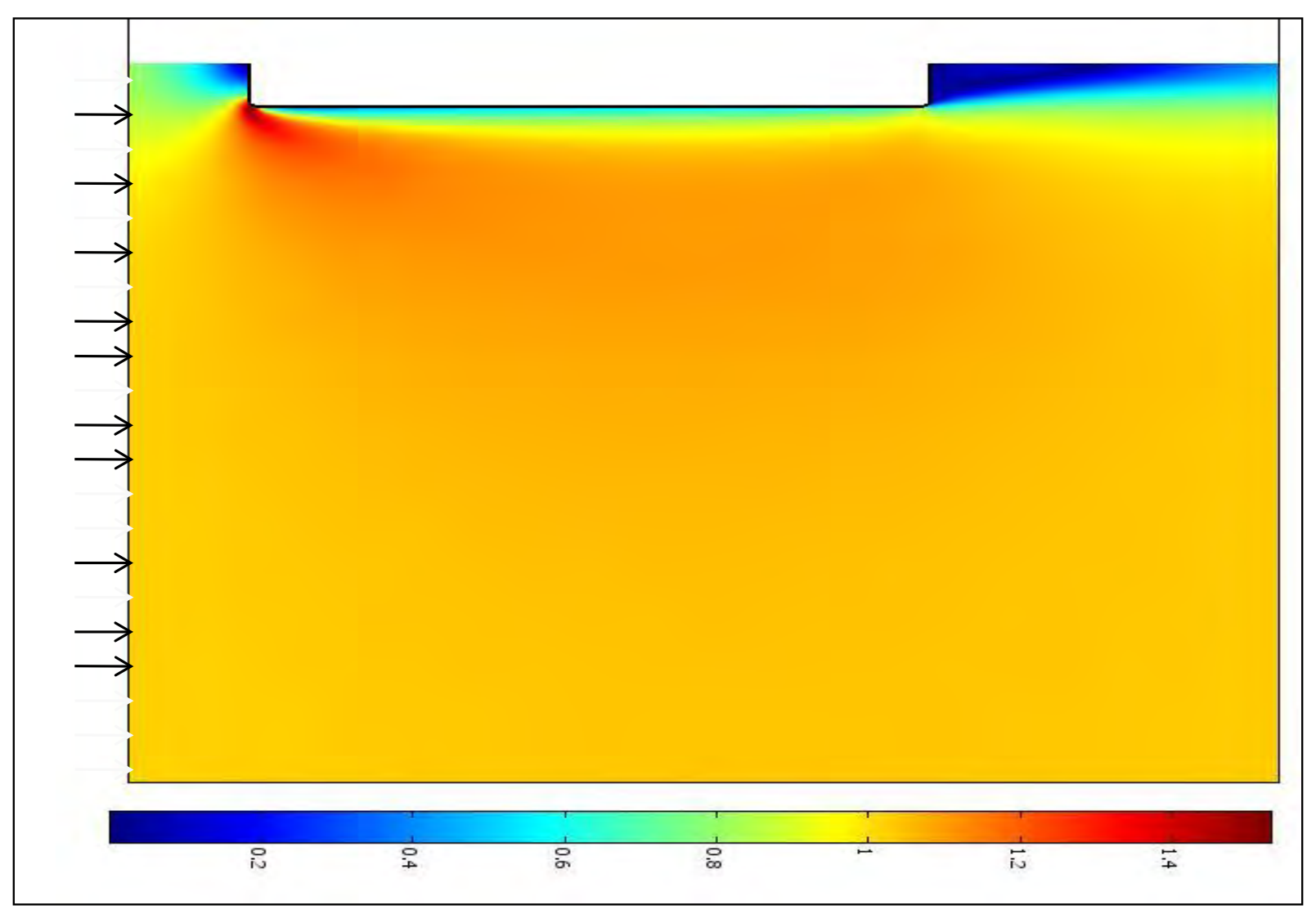
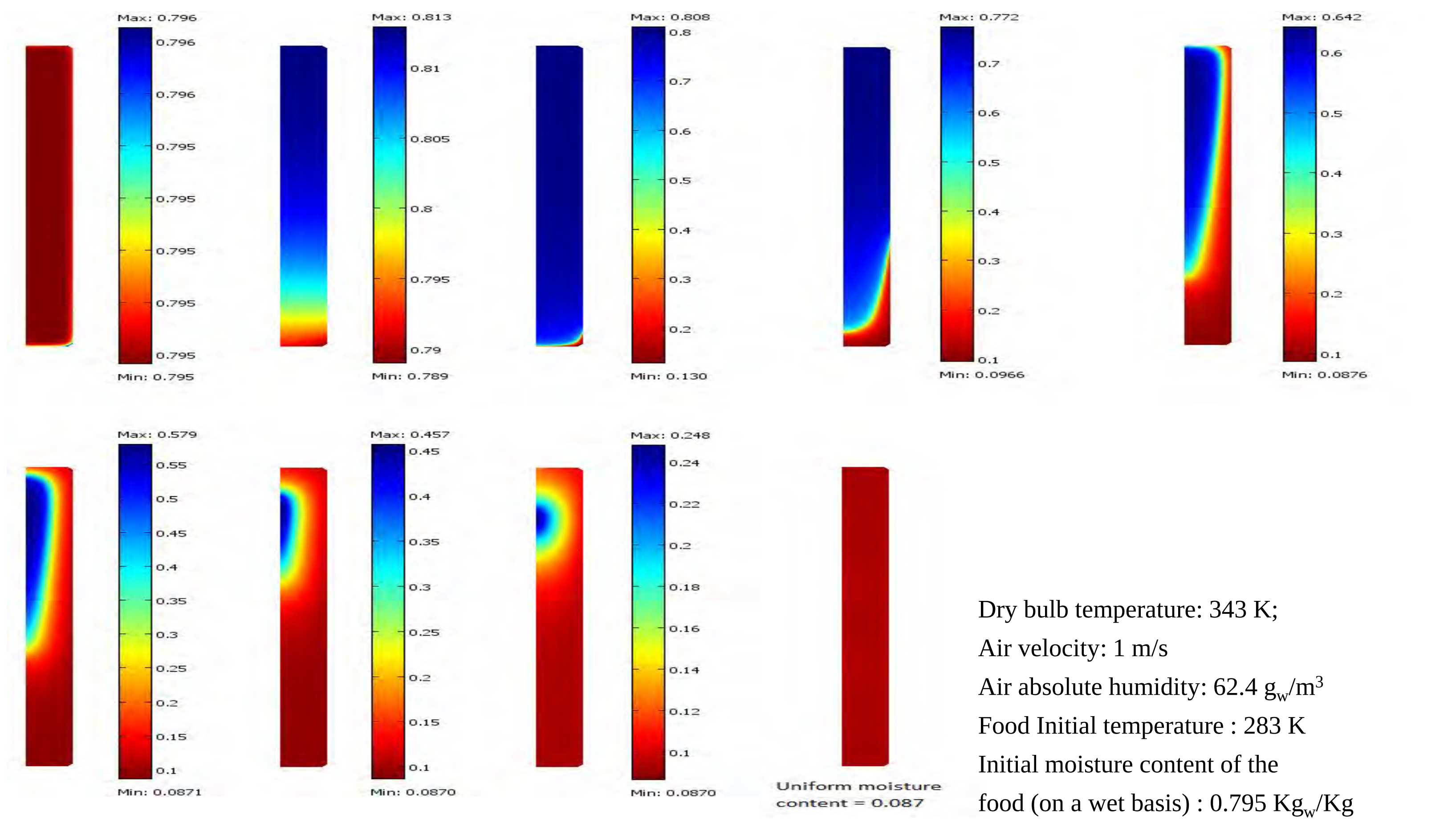
Results:Some of the results obtained by food drying simulations are showed in Fig.3.

Optimization Problem: It is necessary to identify a definite set of operating conditions that has to be chosen so as to achieve, at the same time, high quality and safe dried foods.





Dry bulb temperature: 343 K;
Air velocity: 1 m/s
Air absolute humidity: 62.4 g_w/m^3
Food Initial temperature : 283 K
Initial moisture content of the food (on a wet basis) : 0.795 Kg_w/Kg

Figure 3. Velocity field in air and time evolution of potato moisture content (wet basis)

Identification of the design variables that are to be controlled:
Average moisture content of the food; microbial population, food quality (color degradation). Also the input variables are known or can be fixed

Mathematical model describing the process behavior:
The already-described combination of the transport phenomena model, of the product decontamination model predicting the microbial inactivation kinetics of Listeria monocytogenes and of the model describing the kinetics of color changes

Requirements that must be met:
Proper decontamination of the final product (attention to the critical points of each exposed surface, in particular the rear one); high organoleptic properties of dried potatoes; attainment of a limit value of food moisture content corresponding to water activity values smaller than a definite threshold

Definition of the objective function:
Analysis of different scenarios

The optimization technique:
A derivative-free method CDOS (Conjugate Direction with Orthogonal Shift) available in Maple ☐Proper integration between Comsol and Maple

Minimize $\overline{X_b}$;
$t \in [0, 180\text{ min}]$, $H \in [20, 50]$, $Ta \in [323\text{ K}, 363\text{ K}]$;
Subject to : $N/_{N0} \le 10^{-6}$; $\Delta a \le 3$; $\Delta b \le 3.5$

$t = 179$ min, $H = 25.6\%$,
$Ta = 356.27$ K; $\overline{X_b} = 0.66$
$N/_{N0} = 1.42\ 10^{-16}$;
$\Delta a = 4.0$; $\Delta b=4.0$

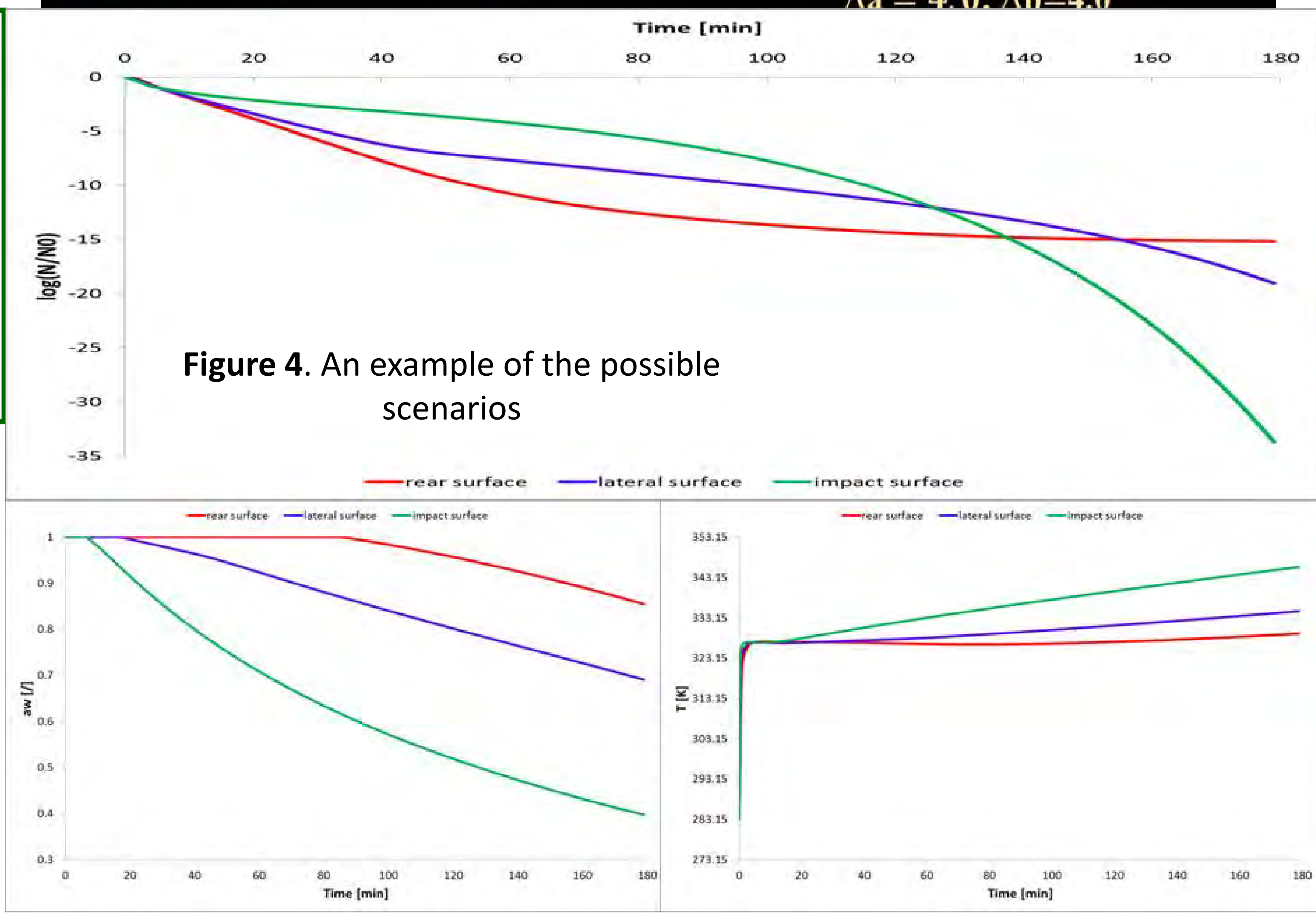


Figure 4. An example of the possible scenarios

Conclusions:A general predictive tool given as a combination of a transport phenomena model, of a product decontamination model and of a model describing the kinetics of color changes (quality parameter) was developed

An optimization model was also formulated; a set of operating conditions that allows attaining specific control objectives represented by the determination of a trade-off condition between quality and safety was determined. It is therefore possible to minimize expensive and time-consuming pilot test-runs.

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