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

S. Curcio[*1], M. Aversa[2]
[1,2]University of Calabria
*Corresponding author: Department of Engineering Modeling, via P. Bucci cubo 39 C, 87036 Rende (CS), Italy, stefano.curcio@unical.it

Abstract: The aim of this work was the development of a predictive model aimed at identifying a proper control strategy of food drying process. In particular, it was intended to determine the effect of operating conditions both on the color degradation, chosen as a reference quality parameter, and on the microbial spoilage occurring during potatoes drying. A transport model, accounting for the simultaneous transfer of momentum, heat and mass occurring in the drying air and in the food sample, was formulated and coupled both to a product decontamination model, describing the microbial inactivation kinetics of Listeria monocytogenes and to another model aimed at predicting the kinetics of color changes occurring during drying. The proposed model allowed determining, on the basis of a dynamic optimization algorithm, a trajectory of operating conditions that has to be tracked by means of proper control systems so as to optimize the performance of drying process.

Keywords: Food, drying, control, color, microbial.

1. Introduction

In the food industry convective drying is performed to reduce the microbial spoilage and the deterioration reactions (1). The main objective of food drying is, therefore, the product decontamination so as to enhance its safety and to improve its shelf-life. Both the heat effect and the induced reduction of food water content avoid the growth of microbial species since they are incapable to survive below a water activity threshold limit, $a_{w,lim}$ (2).

During thermal drying, food quality is however strongly deteriorated: the loss of water does indeed cause profound modifications to both the mechanical and the structural properties of food, together with a degradation of many essential attributes, such as color. Color is usually considered as the key quality attribute of foodstuffs due to its relation with flavor and aroma (3).

On the basis of the above reported discussion, the optimization of drying process may consist in the identification of a set of operating conditions capable of guaranteeing the safety and quality of dried foods in the cheapest way. Usually, dynamic optimization, actually resulting in a trajectory of operating conditions that has to be tracked by means of proper control systems, is to be preferred over other types of methodologies (4).

The control of inherent non linear and unsteady state processes, such as food drying, is a challenging area of research; nonlinear control plays an increasing important role in process control engineering and, within this frame, neural networks may represent an attractive alternative to traditional model-based control techniques (5,6).

In this work, a theoretical model was proposed to predict vegetables drying behavior over a wide range of operating conditions. The proposed model, accounting for the simultaneous transfer of momentum, heat and mass both in the drying air and in the food sample, was capable of describing the bacterial starvation and the color degradation occurring during food drying. The bacterial starvation and the color degradation were chosen as model outputs since they represent the actual controlled variables of the process under study, due to the strong relationships existing between them and both the reduction of water content, determining microorganisms starvation, and the dried food quality, expressed in terms of its external aspect.
In particular, it was intended to determine the effect of operating conditions both on the color degradation, chosen as a reference quality parameter, and on the microbial spoilage occurring during potatoes drying. It is well known, in fact, that the exploitation of drastic

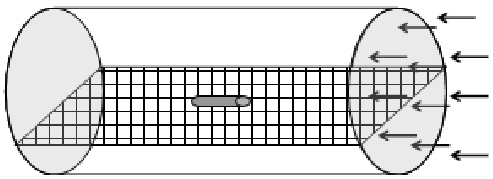

Figure 1. Schematic representation of the drying chamber.

operating conditions, although improving food safety, may induce major thermal damages, thus determining a significant worsening of dried products quality. On the contrary, the utilization of mild operating conditions does certainly improve the organoleptic properties of dried foods, but could not assure a proper decontamination of the final product. It is, therefore, necessary to identify the set of operating conditions that are to be chosen so as to achieve, at the same time, high-quality and safe dried foods.

2. Model development

When dry and warm air flows around a moist and cold food sample, two different transport mechanisms simultaneously occur: heat is transferred from air to the material water, instead, is transferred from food to air. Within the solid material, heat is transported by conduction and convection; the transport of water, as liquid, is due to both gas pressure and capillary pressure gradients, whereas vapor is transferred by pressure and concentration gradients.

To develop the present theoretical model it was assumed that (7): a) capillary pressure 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. b) The term containing the pressure driven flow in vapor transfer equation was neglected and the molecular diffusion was considered as the prevailing mechanism. c) The contribution of convection to heat transport was considered negligible as compared to conduction. d) Evaporation occurred over the entire food domain and also at food outer surfaces. e) 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. f) The continuity of both heat and mass fluxes occurred at the food/air interfaces. g) All the phases, i.e. solid, liquid, and gas, were continuous and were in local thermal equilibrium. h) The vapor pressure was expressed as a function of both temperature and moisture content. i) The turbulent momentum transfer referred to drying air flowing in the drying chamber around the food sample was described by the k-ω model.

On the basis of the above assumptions, a system of transport equations referred to both drying air and food was obtained to model the behavior of the drying chamber shown in Fig. 1.

In particular, the unsteady-state mass and energy balance equations referred to the transport of liquid water and of vapor in the food sample were:

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

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

where C_w was the liquid water concentration, C_v was the vapor concentration,   was the volumetric rate of evaporation, D_w and D_v were the capillary diffusivity of water and the effective diffusion coefficient of vapor in food, respectively.

The energy balance in the food material led, according to Fourier's law, to the unsteady-state heat transfer equation:

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

where T was the food temperature, s was the density of food sample,   its specific heat, k_{eff} was the effective thermal conductivity and λ the latent heat of vaporization of water.

The unsteady-state momentum balance in turbulent conditions (i.e. the so-called Reynolds-averaged Navier-Stokes equations) coupled to both the continuity equation and the transport equations for k and ω, the energy balance (accounting for both convective and conductive contributions) and the mass balance (accounting for both convective and diffusive contributions) were used to model the transport phenomena in the drying air:

Momentum balance and continuity equation:

$$\partial \rho_a / \partial t + \underline{\nabla} \cdot \rho_a \underline{u} = 0 \tag{4}$$

$$\rho_a \partial \underline{u} / \partial t + \rho_a \underline{u} \cdot \underline{\nabla} \underline{u} + \underline{\nabla} \cdot \left(\overline{\rho_a \underline{u}' \otimes \underline{u}'} \right) = -\underline{\nabla} p + \underline{\nabla} \cdot \left[\eta_a \left(\underline{\nabla} \underline{u} + (\underline{\nabla} \underline{u})^T \right) \right] \tag{5}$$

$$\rho_a \partial k / \partial t + \rho_a \underline{u} \cdot \underline{\nabla} k = \underline{\nabla} \cdot [(\eta_a + \sigma_k \eta_t)(\underline{\nabla} k)] + \frac{\eta_t}{2} \left(\underline{\nabla} \underline{u} + (\underline{\nabla} \underline{u})^T \right)^2 - \beta_k \rho_a k \omega \tag{6}$$

$$\rho_a \partial \omega / \partial t + \rho_a \underline{u} \cdot \underline{\nabla} \omega = \underline{\nabla} \cdot [(\eta_a + \sigma_\omega \eta_t)(\underline{\nabla} \omega)] + (\alpha \omega / 2k) \eta_t \left(\underline{\nabla} \underline{u} + (\underline{\nabla} \underline{u})^T \right)^2 - \beta \rho_a \omega^2$$
(7)

where p was the pressure within the drying chamber, u was the averaged velocity field, ⊗ was the outer vector product,   was the fluctuating part of velocity field and β_k, σ_k , σ_ω, α, β were constants (8).

Heat balance equation:

$$\rho_a C_{pa} \partial T_2 / \partial t - \underline{\nabla} \cdot (k_a \underline{\nabla} T_2) + \rho_a C_{pa} \underline{u} \cdot \underline{\nabla} T_2 = 0 \tag{8}$$

where T_2 was the air temperature,   was its specific heat and k_a was the air thermal conductivity, actually comprised by both a laminar and a turbulent contribution to energy transport by conduction.

Mass balance equation:

$$\partial C_2 / \partial t + \underline{\nabla} \cdot (-D_a \underline{\nabla} C_2) + \underline{u} \cdot \underline{\nabla} C_2 = 0 \tag{9}$$

where C_2 was the water concentration, as vapor, in the air and D_a was the diffusion coefficient of vapor in air; also in this case, both a laminar and a turbulent contribution were considered to express mass transfer due to a diffusion mechanism.

It is worthwhile remarking that the physical and the transport properties of both food and drying air were expressed in terms of the local values of both temperature and moisture content.

A set of initial conditions 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, initially, the value of 298 K and that the water concentration, C_{20}, was equal to 0.642 mol/m3 (corresponding to a relative humidity, U_{r0}, of 50%). It was also assumed that, before the drying process occurred, the air was stagnant (i.e.) and that the pressure in the drying chamber, p_0, was 1 atm. The initial value of food temperature, T_0, and of its moisture content, U_0, were set equal, respectively, to 283 K and to 0.785 kg H2O/kgw (on wet basis) corresponding to 3.65 kg H_2O/kg_{ds} (on dry basis). It is worthwhile remarking that the present transport model was flexible and allowed changing the values of T_{20}, C_{20}, T_0 and U_0, so as to simulate drying process behavior in a wide range of initial conditions having a physical significance.

As far as the boundary conditions were concerned, at the food-air interface, where no accumulation occurred, the continuity of heat and water fluxes was imposed. Moreover, a thermodynamic equilibrium at the air/food interface was formulated and expressed in terms of the water activity, so to account also for the effects of physically bound water. The values of temperature, of vapor concentration and of velocity of the air entering the oven were fixed before performing each simulation and represented three input parameters that could be deliberately changed in order to analyze the system behavior over as wider as possible range of process and fluid-dynamic conditions.

Moreover, it was assumed that at the dryer walls air temperature and its vapor concentration were equal to the corresponding values measured at the drier inlet. These two conditions are 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, conduction and diffusion were neglected in favor of convection, which prevailed. Finally, the boundary conditions for momentum balance at the solid walls were expressed in terms of a logarithmic wall function.

It is worthwhile observing that the formulated theoretical model could be considered as very general since it did not make use of any transport coefficient aimed at estimating the heat and mass fluxes at the food/air interfaces.

The above-described transport model, as represented by Eqs. 1-9 together with the corresponding boundary and initial conditions, was capable of describing the time evolution of drying process but actually did not give any indication about the progress of product decontamination and about the quality of dried vegetable.

For this reason, two additional models were developed and included in the more general transport model with the aim of relating the calculated local values of both moisture content and temperature in the food to microbial inactivation and to color degradation, as determined by the operating conditions chosen to perform the drying process.

In particular, product decontamination was described considering the microbial inactivation kinetics of Listeria monocytogenes expressed as a function of temperature and water activity (2). Among the microorganism that might proliferate on vegetables surface, Listeria was definitely the most studied due to the safety problems that may arise if it is not properly inactivated during processing.

The following "primary" model, i.e. a model describing the microbial population as a function of time, was chosen:

$$\frac{dN}{dt} = -k_{\max} \cdot \left(\frac{1}{1+Cc}\right) \cdot N \qquad (10)$$

where N represented the microbial population, kmax was the so-called specific inactivation rate and Cc was the physiological state of cells and was a function of time as well.

$$\frac{dCc}{dt} = -k_{\max} \cdot Cc \qquad (11)$$

Eqs. 10-11 could be integrated knowing the initial microbial population, N_o, and the initial value of the parameter C_c that for Listeria monocytogenes in macerated potatoes was estimated to be constant and equal to 10^6 and to 10^{-4}, respectively (2).

A "secondary" model was then identified to relate kmax to the local values, as calculated by the above-described transport model, of both temperature and water activity on the food surface:

$$k_{\max}(T, a_w) = \frac{\ln 10}{1.8} \exp\left(\frac{\ln 10}{7.11}(T-60)\right) \cdot \exp\left(\frac{\ln 10}{0.231}(a_w - 1)\right) + 0.221 \qquad (12)$$

where T was expressed in °C.

To predict the kinetics of color changes occurring during drying the model proposed by Krokida et al. (9) was exploited. This model describes the color changes kinetics in terms of the so called Hunder parameters, i.e. redness (a), yellowness (b) and lightness (L). Each of these parameters obeyed a first order kinetics that was given by the following general equation:

$$\frac{C - C_e}{C_0 - C_e} = \exp(-k_c t) \qquad (13)$$

where C was each of the color parameter (a, b, L), C_0 and C_e were their corresponding initial and equilibrium values, k_c was a rate constant and t was the drying time. The dependence of color parameters on the operating conditions, i.e. the dry bulb temperature, T_a, and the relative humidity, H, of drying air, was taken into consideration through the effect that T_a and H determined on both the equilibrium value and the rate constant, according to the following equations:

$$Ce = C_{eo}(T_a/70)^{a_T}(H/30)^{a_H} \qquad (14)$$

$$k_c = K_{c0}(T_a/70)^{m_T}(H/30)^{m_H} \qquad (15)$$

The empirical parameters of Eqs. 14-15 were actually available for potatoes.

The system of PDEs and ODEs as represented by Eqs. 1-15 was solved by the Finite Elements Method implemented by the commercial package Comsol Multiphysics 4.2, defining a proper two-dimensional domain representing either the potato sample or the drying chamber.

The proposed model allowed simulating potatoes drying process and to identify the corresponding microbial deactivation and color changes.

3. Results

The proposed transport model allowed determining, on the basis of a definite set of the input parameters, namely the dry bulb temperature (Ta), the relative humidity (H) and the feed velocity (u_0) of the drying air, the actual time evolutions of both moisture content and temperature within the food.

Fig. 2 and 3 showed the time evolution of potato moisture content (on a dry basis) and of temperature, respectively. 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, moisture content 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 well above the wet

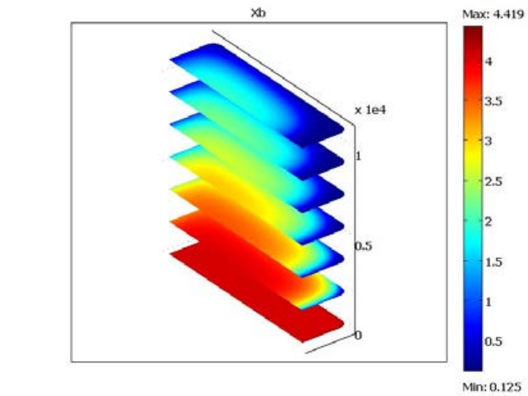

Figure 2. Time evolution of potato moisture content during drying (T_a = 70°C, H = 30%, u_0 =2.2 m/s).

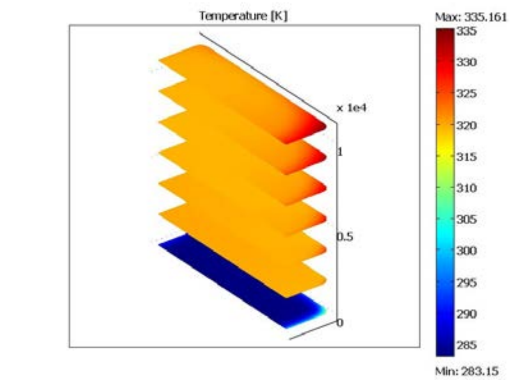

Figure 3. Time evolution of potato temperature during drying (T_a = 70°C, H = 30%, u_0 =2.2 m/s).

bulb temperature. The low thermal conductivity of the dry surface region, together with evaporation, led to a significant drop in temperature from the surface to the food core (fig. 3). 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.

The present transport model allowed determining, in a wide range of process and operating conditions that could be changed varying the input parameters, the local values of both water activity and temperature on food external surfaces. In this way, it was possible to estimate, according to Eqs. 10-12, the actual reduction of Listeria monocytogenes population. The corresponding colors changes were instead determined, according to Eqs. 13-15, as a function of process time and of the chosen values of T_a and H.

Fig. 4 showed the time evolution of food Hunder parameters a and b. Both the parameters increased as drying proceeded, thus indicating a significant quality degradation of food organoleptic characteristics.

Fig. 5 showed, as a function of air dry bulb temperature, the decrease both of Listeria population and of temperature on a point laying on the food surface where drying air actually impinged. It could be observed a significant enhancement of food safety as air temperature increased from 333 K to 353 K. It is worthwhile observing that decontamination actually occurred to a very limited extent when the dry bulb temperature was equal to 333 K; during the initial period of food drying, i.e. when free water was removed, the food surface temperature was almost uniform and equal to the wet bulb temperature, which, in the present case, was rather low and equal to about 312 K.

It is worthwhile observing that the exploitation of drastic operating conditions, namely high dry bulb temperatures and low

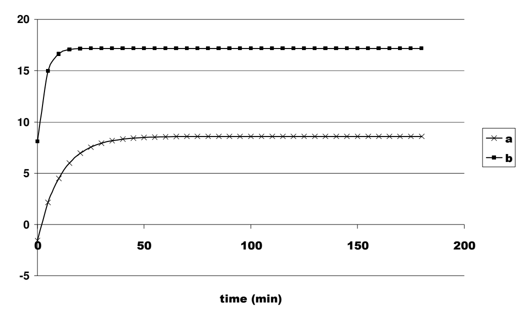

Figure 4. Time evolution of a and b Hunder parameters during drying (T_a = 70°C, H = 30%, u_0 =2.2 m/s).

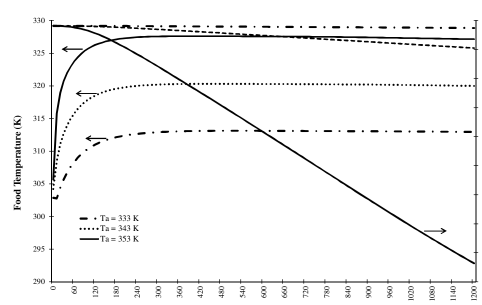

Figure 5. Time evolution of Listeria population during drying (H = 30%, u_0 =2.2 m/s).

values of relative humidity, had the following effects: the drying rate was high and the process went to completion faster; the reduction of microbial population was more efficient and food safety was improved; the organoleptic characteristics of food tended to deteriorate, thus determining a significant worsening of dried products quality. On the contrary, the utilization of mild or very mild operating conditions, namely low dry bulb temperatures and intermediate values of relative humidity, determined an opposite behavior: the organoleptic properties of dried foods did certainly improve, but a proper decontamination of the final product could not be assured. It was, therefore, necessary to identify a definite set of operating conditions, possibly changing during drying process, that had to be chosen so as to achieve, at the same time, high quality and safe dried foods.

A process optimization approach was therefore exploited, defining a proper objective function which was minimized by a commercial package called AIMMS. The developed optimization model, tested over a very wide range of operating conditions, allowed identifying a trajectory of operating conditions, actually variable with time, that would be advisable to track so as to achieve specific control objectives typical of industrial drying process.

4. Conclusions

The proposed model represented a general predictive tool capable of describing the food drying process in those conditions in which internal evaporation was significant and could not be neglected. Heat and mass conservation laws, for both food and air, together with momentum transfer in turbulent conditions (for air only) were coupled, by means of a proper set of boundary conditions. The time evolutions of drying were predicted with no a priori limitation for irregular or complex-shaped systems.

The proposed model is particularly useful for those situations in which either semi-empirical correlations are not currently available (i.e. complex food geometries) or operating conditions are changed during drying process. Moreover, the model can also be used to determine which set of operating conditions would enhance the quality and the safety of the final product, thus minimizing expensive and time-consuming pilot test-runs. It is, in fact, possible to predict the spatial moisture profiles at all times, thus allowing the detection of the regions where either high values of moisture content or low values of temperature can promote microbial spoilage.

Finally, a proper optimization model was developed and, then, tested over a very wide range of operating conditions; a trajectory of operating conditions, actually variable with time, was eventually identified so as to achieve specific control objectives represented, for instance, by the determination of a trade-off condition between quality and safety.

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