STUDIA UBB CHEMIA, LX, 1, 2015 (p. 157-163)
(RECOMMENDED CITATION)

MODEL PREDICTIVE CONTROL OF THE TEMPERATURE IN DRYING FOOD PRODUCTS

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ABSTRACT. The present work addresses the improvement of the drying process of food products by controlling their temperature, using the model predictive control strategy. Forced convection drying with hot air is considered for the slab shaped food product, described in a 2D geometry. Control is based on the model describing the space and time change of the temperature and concentration of water vapours and liquid water in the porous solid together with pressure, drying air velocity, moisture concentration and temperature change in the drying air. Model predictive control of the temperature inside the food slab is simulated using a typical ramp-constant temperature setpoint and results show the incentives of the proposed control strategy, aimed to conform to the drying program of the temperature for preserving the drying product specific quality.

Keywords: *Model predictive control, forced convection drying, food slab*

INTRODUCTION

The market driven forces of the food industry pose important challenges for the food producers, as the demanded quality and quantity of the products are facing severe competition between companies and continuously growing customers' expectations. Originally, the drying process of food products emerged from the traditional and natural way of preserving food for its consumption at a subsequent occasion with respect to their harvest or production time. Later, the reduction of the transportation and storage costs, associated to the relative large period for preserving their quality and the marked demands, have placed the dried food in a contest with the frozen or canned food products. Nevertheless, conserving the organoleptic properties of the dried food is not a trivial task and usually an optimal moisture content is

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desired to accomplish this requirement. When the water content is too large the food may be affected by bio-transformations by the growth of bacteria, yeasts or mould, and decomposes. The overdried food product may change or lose its aroma and other appreciated nutritive properties (e.g. each fruit and vegetable has a critical temperature above which a scorched taste develops).

An overview of the drying technology reveals that there are tens of thousands of products that need to be dried in over a 100 variants of dryers [1]. Mujumdar, Kowalski and Murugesan presented comprehensive and specific studies on the air convective drying of porous materials [2-4]. Representative drying investigations of the food has been carried out by Barbosa-Canovas, Kaya and Ruiz-Lopez [5-7].

Both traditional and new technological solutions require appropriate control systems for ensuring their economic efficiency and quality standards. Model Predictive Control (MPC) is the most promising and appreciated advanced process control methodology used in chemical engineering applications, in standalone or coupled with PID control structures and implemented in either decentralized, supervisory or in multivariable control configurations.

Based on these assumptions, the investigations and results presented in the paper show the way MPC may be used to control the food drying process by imposing a prescribed ramp-constant temperature setpoint for the drying food temperature. The case study of convective drying of carrot food slabs is investigated based on the experimental drying data reported by De Bonis et al. [8] and the preliminary traditional control simulation approach using the PI controller, presented in [9].

RESULTS AND DISCUSSION

The first step in developing the MPC drying application was the selection and software implementation of the mathematical model, which was further used as intrinsic component for the control strategy. The model used in this work consists in the drying model presented by De Bonis [8], with appropriate changes to make it suitable for implementation for control investigations in the COMSOL Multiphysics CFD software [9].

The model is a conjugate one, considering both the transient mass and heat transfer of water in the porous solid body and the surrounding air, together with the momentum transfer describing the flow and pressure of the fluid phase. An important particularity of the model is the irreversible first order kinetics accounted for the vapour and liquid water production or depletion and transport. This approach allows the computation of the moisture, temperature and flow fields and avoids the limitations of the boundary layer assumptions with its associated need for empirical heat and mass transfer coefficients evaluation [8]. The heat transfer from the drying air to the solid surface is ruled by forced convection, while the heat transfer form the exterior to the interior of the solid is governed by the conduction mechanism. Vaporisation of the liquid water takes place both on the surface of the solid and in its inner volume. Water is basically transported in three ways: by diffusion, due to the liquid water concentration difference between the solid interior and its surface, by capillarity and by diffusion of water vapours from the inner part of the porous solid to its surface, due to vapours pressure differences [8, 9]. The main assumptions inherent to the model are: laminar flow of the drying air; density, specific heat and thermal conductivity of the solid and diffusivity of liquid water and vapours in the solid considered to be moisture dependent [8]; lack of any body force; inclusion of the capillary transport in the diffusion coefficient and assumption of the same diffusivity of the liquid water and vapours in the porous solid. The two considered domains are the solid body and its surroundings, as presented in figure 1.

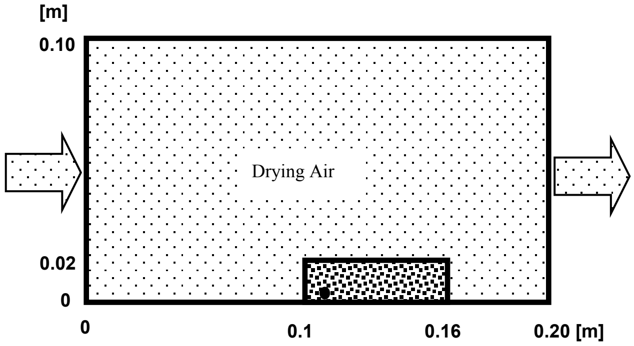

Figure 1. Geometry of the food slab and its associated surroundings.

Appropriate equations describe the two main domains of the food slab and its air surroundings. They are [8]:

$$\frac{\partial c_l}{\partial t} + \nabla \cdot (-D_{ls} \nabla c_l) = -K c_l, \tag{1}$$

$$\frac{\partial c_v}{\partial t} + \nabla \cdot (-D_{vs} \nabla c_v) = -K c_v, \tag{2}$$

$$\rho_s c_{ps} \frac{\partial T}{\partial t} + \nabla \cdot (-k_s \nabla T) = \dot{e}, \tag{3}$$

$$\frac{\partial c_v}{\partial t} + \nabla \cdot (-D_{va} \nabla c_v) = \mathrm{u} \cdot \nabla c_v, \quad (4)$$

$$\rho_a \left(\frac{\partial \mathrm{u}}{\partial t} + \mathrm{u} \cdot \nabla \mathrm{u}\right) = -\nabla p + \mu \cdot \nabla^2 \mathrm{u}, \quad (5)$$

$$\rho_a c_{pa} \frac{\partial T}{\partial t} + \nabla \cdot (-k_a \nabla T) = -\rho_a c_{pa} \mathrm{u} \cdot \nabla \mathrm{T}. \quad (6)$$

The following notations have been used: c_l and c_v are the concentrations of liquid water and vapours; D_{ls}, D_{vs}, D_{va}, are the diffusivities of the liquid water, vapours in the porous solid and, respectively, the vapours diffusivity in the air; ***u*** is the air velocity vector; *p* is the pressure; k_s and k_a are the thermal conductivities in the porous solid and air; $\dot{e}$ is the cooling rate due to evaporation ($\dot{e}=\Delta h_{vap} M_l K c_l$, with Δh_{vap} the latent heat of vaporisation and M_l the water molecular weight), ρ_s and ρ_a are the solid and air densities, c_{ps} and c_{pa} are the specific heats for the solid and air phases; μ is the dynamic viscosity; $K=K_0 e^{-Ea/RT} K_1^{\alpha}$ is the adopted Arrhenius type evaporation relationship [10, 11]. In the last relationship K_0 is a constant determined using experimental data, E_a is the activation energy [11], K_1 is a ratio of the process temperature to the reference temperature and α is a dimensionless temperature factor. The boundary conditions for the equations (2), (3), (4) and (6) account for full continuity for the vapours mass and temperature on the solid surface, excepting the bottom surface.

Model predictive control is the most industrial applied advanced control strategy in process engineering applications, very appreciated for its optimal character, predictive feature, preview ability and straightforward capability of incorporating constraints in the control law [12].

The present paper investigates the MPC control of the temperature in the drying product by manipulating the inlet drying air temperature. The location of the point where the solid temperature is controlled was chosen on the basis of its sensitivity to the temperature changes in time and is described by the coordinates of (0.11, 0.0025) [m], as indicated in figure 1. According to the practice oriented considerations the desired change of the solid temperature has the form of a ramp-constant time change. This temperature setpoint profile is providing a smooth removal of the water from the drying solid, avoiding steep changes that may affect the shape, structure or organoleptic characteristics of the final product.

The MPC temperature control is presented in figure 2. The controller uses an adaptive linearized model of the process obtained by identification based on simulation data from the nonlinear CDF model with time changing inlet drying air temperature.

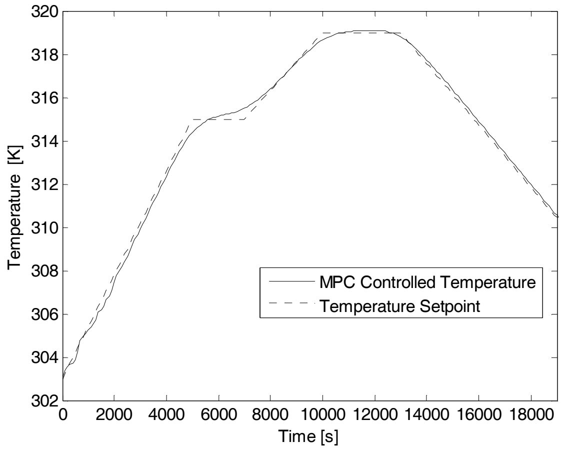

Figure 2. MPC controlled temperature in the drying solid.

The results show the capability of the MPC controller to bring the temperature close to its desired setpoint. It may be also noticed the preview potential of the controller that produces the predictive change of the temperature according to the future desired changes of the temperature setpoint. The liquid water concentration in the aforementioned porous solid point is presented in figure 3.

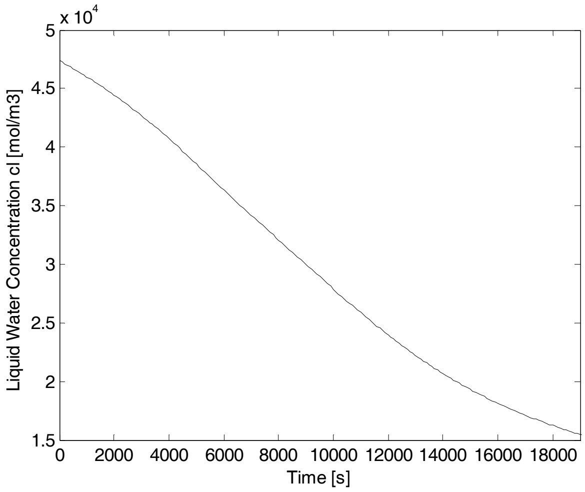

Figure 3. Change of the liquid water concentration in the drying solid.

The MPC controller was tuned such as to provide good control performance all over the range of the temperature setpoint program.

CONCLUSIONS

The distributed parameter mathematical model and the associated dynamic simulator development for the forced convection of the food slab drying process revealed the complex time and space behavior of the liquid and the vapor water content together with the change of the temperature in the porous solid and its surrounding drying air region. Drying process control based on the MPC algorithm has been investigated by controlling the temperature in the drying solid according to a ramp-constant temperature setpoint program. The control results show the efficiency of the proposed temperature control strategy both with respect to the offset and the setpoint tracking, while taking advantage of the prediction and preview capability of MPC. The simulator can be further used for the development of multivariable MPC control of the drying process in order to obtain improvement of the product quality, reduction of the energy consumption and shorter operation time. Based on new experimental data and suitable adjustments the simulator can be used for investigating the improvements of the convective drying in other food products of particular geometries.

EXPERIMENTAL SECTION

The mathematical model and simulator have been validated with experimental data from [7] and [8]. Detailed simulation results have been presented in previous work [9], for the temporal and spatial fields of main variables, showing values in agreement with the results reported in [8]. Initial air inlet temperature of $T_0=353\ K$, moisture of $c_v=7\ mol/m^3$ and velocity of $u=3\ m/s$ have been considered in the simulations. The following numerical constants have been used: $K_0=7000\ s^{-1}$, $E_a=48.7\ kJ/mol$, $\alpha=0$, $c_{l0}=47\ kmol/m^3$ (in the solid substrate), $T_{0s}=303\ K$ and $D_{va}=2.55\ 10^{-5}\ m^2/s$, together with moisture dependent expressions: $c_{ps}=1750+2345(X/(1+X))\ J/(kg\ K)$, $k_s=0.49+0.443exp(-0.206X)\ W/(m\ K)$, $D_{vs}=D_{ls}=2.8527\times10^{10}exp(0.2283369X)\ m^2/s$, $\rho_s=440.001+90X\ kg/m^3$, where X is the solid mass moisture content (on dry basis). The model equations for the drying simulator have been implemented in COMSOL Multiphysics CFD software. The drying control study has been performed in Matlab-Simulink using a special developed application for running the CFD nonlinear dryer model. MPC controller used the following tuning parameters: sampling time $T_s=100\ s$, prediction horizon $p=20T_s$, control horizon $m=8T_s$, weight of the manipulated variable rate $uwt=0.5$ and the controlled variable weight $ywt=1$.

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