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Combined convective and microwave assisted drying: Experiments and modeling

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ABSTRACT

The drying process is largely used in many different industrial applications, such as treatment of foods, production of cosmetics and pharmaceuticals, manufacturing of paper, wood and building materials, polymers and so on.

Physical and mathematical models can constitute useful tools to establish the influence of the main process variables on the final product quality, in order to apply an effective production control. In this work, simulation model was developed to describe combined convective/microwave assisted drying. In particular, a multi-physics approach was applied to take into account heat and two mass balances (for liquid water and for water vapor) and Maxwell's equations to describe electromagnetic field propagation. Potato matrix was selected as food material; a waveguide with a rectangular cross section, equipped with a hot air circulator device, was used as microwave applicator. The proposed model was found able to describe the process, being thus a useful tool for design and management of the process itself.

1. Introduction

Drying is a common method of food preservation, used from the ancient times. Drying process involves the simultaneous transfer of heat and matter, i.e. heat and mass exchanges between the product under processing and the surrounding bulk. In food treatments, water (moisture) is the liquid phase, contained in solid or semi-solid matrices or liquids, that must to be transferred in a fluid drier, typically dry, warm air if convective methods are used.

The removal of moisture prevents the growth and reproduction of micro-organisms causing decay and minimizes many of the moisture-mediated deteriorative reactions. It brings about longer periods of storage, substantial reduction in weight and volume, which means minimizing packing, storage, and transportation costs and enables storage of the product under ambient temperatures.

The types of dryers used affect product characteristics and cost, so to reach a certain goal in product quality and productivity the choice of appropriate dryer is very important. Drying technology had evolved through in four groups or generations of drying methodologies/devices (Vega-Mercado et al., 2001). Drying technology that used microwaves and RF is proposed as an innovative process of the fourth generation, after convective methodologies (cabinet, kiln, bed, conveyor, and spray drier and drum drier in the first and the second process generations, respectively) and freeze dehydration and osmotic methods (third generation). Indeed hybrid methodologies receive great interest because they can combine advantages of different heating methods to achieve more efficient processes. Convection is the most applied and deeply studied heating method in food treatments, microwaves heating is the emerging technology that allows fast warm up based on dissipative features of food. For these reasons the combination of convective and microwave drying is of great practical interest.

1.1. State of the art

Physical and mathematical models are important to establish the influence of the main process variables on the final product quality, in order to apply an effective production control. This objective may be achieved by making a global model capable of simulating what happens during the process and therefore to predict the values of the desired properties. Several mathematical models have been developed and reported in literature for convective, microwave and microwave convective drying.

Several authors (Chemkhi et al., 2005; Karim and Hawlader, 2005; Migliori et al., 2005; Yang et al., 2001) studied and modeled convective drying processes for different foods. The proposed models consist in mass and heat balances and equations to describe shrinkage phenomena. The main hypothesis being: the medium was considered biphasic (solid and liquid); the initial distributions of moisture and temperature were considered uniform and the

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thermodynamic equilibrium condition at the air-sample interface, which is assumed to coincide with the evaporation front. Barba (2005) reported a mathematical code able to numerically solve a couple of generalized balances of heat and mass transfer equations. The code, after its validation, was applied to describe the heating of foodstuff in DSC (Differential Scanning Calorimetry) investigation. The code was built to manage many different kinds of boundary conditions, variable coefficients, multilayers problems, different kinds of generation terms, including the dielectric power generation which takes place during microwave heating.

Constant et al. (1996) studied a model of simultaneous heat and mass transfer to describe drying with internal heat generation. Then, all the phenomena were taken in account: mass balances, energy balance, phenomenological relations, equilibrium relations, and the appropriate boundary conditions. The agreement between experimental and numerical results was satisfactory. Jansen and Van der Wekken (1991) proposed a mathematical description of the microwave assisted drying process, the model outlined accounted for the desorption isotherm, transport of free water, vapor transport, transport of bound water, mass and heat balances. The electromagnetic field was not evaluated; the measured temperature peak value was used to evaluate power dissipation. Convective drying, dielectric drying and combined convective and dielectric drying were simulated and the results were successfully compared with experimental results. Perre and Turner (1997) presented a model describing mass balance for free and bounded water, heat balance and Maxwell's equations. The match between the experimental and theoretical results was qualitatively consistent. Most importantly, the model was able to predict the occurrence of hot spots and thermal runway within the material. Turner and Jolly (1990) proposed a 1D model describing heat balance, mass balance for liquid water and they showed that by using dielectric properties dominated by moisture dependence or by temperature dependence, the use of microwaves could be justified during the initial stages of drying or in the latter stages of drying, respectively. Their findings were purely theoretical, since no experimental data were used for validation. Kowalski et al. (2010) presented a mathematical model of microwave-convective drying and its validation. They considered a three phase material and neglected deformation (shrinkage). Energy and mass balances are reported. They considered that the amount of microwave energy absorbed by the drying material decayed exponentially with distance. The theoretical results reflect qualitatively well the experimental data. Soysal et al. (2006) studied microwave drying of parsley and proposed an empirical fitting of experimental data of microwave drying curves. McMinn et al. (2003) adapted the analytical model proposed by Dincer and Dost (1995) to evaluate the mass transfer characteristics, moisture diffusivity and moisture transfer coefficient of a selected food. Raskesh and Datta (2008) proposed a 3D model composed by Maxwell's equations solved at stationary state inside the oven cavity and sample and momentum, heat and mass transfer inside the sample. The three phases included in the porous media model were solid, liquid water and gas. For momentum balance, Darcy's equation was used for each phase in the porous media. The model formulated by Renshaw (2009) described dehydration of the foodstuff using evaporation, transport phenomena and RF heating. A 2D model was developed considering the following governing equations: incompressible Navier-Stokes for free air flow; Darcy's law for flow inside porous media; mass balance for water, vapor and oil inside the media; mass balance for vapor in free air outside the media; heat balance; Maxwell's equations. The author considered evaporation inside the sample and the electromagnetic field was studied at transient state. Acierno et al. (2004a) analyzed the transport phenomena occurring during microwave heating of a body in a cylindrical microwave single-mode applicator. A transient 1D energy balance equation was adopted to describe the heating processes in presence of chemical reaction, the electromagnetic field was solved in term of TM010 mode (Transverse Magnetic mode, i.e. the magnetic field propagating does not have an axial component) propagation. Heat and mass transfer induced by microwave heating in a multimode closed microwave cavity were experienced and modeled in Acierno et al. (2003), in which wet soil cylinders were irradiated to promote the moisture evaporation for decontamination purposes. A transient 1D energy balance equation was coupled to mass balance to take in account the water (and the energy) losses; the electromagnetic field was modeled by the Lambert-Beer exponential decay; the dielectric properties dependence upon moisture was taken into account by a semi-empirical equation, and it was found to be a very important aspect of the process. Comparison between simulated temperature and residual moisture content profiles and experimental data were found satisfying. These results were used in further studies to built an opened microwave applicator prototype and to develop irradiating work protocols (Acierno et al., 2004b).

Summarizing, in literature a lot of approaches were followed to simulate the microwave and the convective/microwave heating of foodstuff. The most common approximations are:

(1) to consider the matrices dielectric properties as constants, which allows to separate the electromagnetic problem from the heat and mass transfer phenomena, since the dielectric properties were taken as not variable with temperature and moisture content, and then to consider only the transport phenomena in transient regime. Actually, the dielectric properties are known to be very strong functions of temperature, water and ions content of the matrices;
(2) to use approximate solutions for electromagnetic propagation (the Lambert-Beer law, the analytical solution to Maxwell's equations in void waveguides), which simplifies a lot the equations to be solved, but which is often very different from the real conditions.

1.2. Aim of the work

The objective of this work is to develop a simulation model to describe the combined convective and microwave assisted drying process for a selected food material and dryer, taking in account of the dependence of dielectric properties from the conditions of foodstuff (temperature and water content), and solving both the heat and mass transport equations and the Maxwell's equations in transient regime.

2. Material and methods

The experimental tests were carried out in the frame of a previous work, and the results were published elsewhere (Holtz et al., 2010). In this section the work done was briefly summarized. Furthermore, the tools used for the modeling and simulation steps were presented.

2.1. Material

Potato matrix is selected as food model. Potato parenchyma is structurally less complex than for other vegetables and its physical properties, essential for defining assumptions for calculations, are well documented (Barba, 2005; Khraisheh et al., 2000; Wang and Brennan, 1992, 1993). Thus it is suitable to drying study purposes. Potatoes were bought at a local food store and had an initial moisture content of 3.84 $kg_{water}/kg_{dry\ matter}$ (79.3% on wet basis), other physical properties were reported in Table 1.