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Formulation of a 3D conjugated multiphase transport model to predict drying process behavior of irregular-shaped vegetables

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ABSTRACT

In this paper, a conjugated multiphase transport model aimed at predicting the behavior of food convective drying was formulated. The model referred to a 3D spatial domain in which two samples were exposed to drying air, flowing around the foods. The system of non-linear, unsteady-state, partial differential equations modeling the simultaneous transfer of momentum, heat and mass, occurring in both the drying chamber and the food samples, was solved by a finite elements formulation. The present study was intended to cover missing aspects in scientific literature dealing with food drying modeling. It represents, in fact, one of the first attempts to rigorously describe, for given process operating conditions, the transport phenomena involved during drying process of irregular-shaped vegetables, considered as multiphase hygroscopic porous media with different characteristics. In addition, one of the major contributions offered by this work regarded the possibility of identifying, on food samples surfaces, the points where the local values of both water activity and temperature might determine an inefficient or, even, an unsatisfactory abatement of microbial population, thus causing microbial spoilage.

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1. Introduction

Drying represents one of the most important techniques for preservation of biological products (Triphaty and Kumar, 2008). In convective drying, actually the most common process exploited in industry to dry foods and biomaterials, hot air, flowing around the samples, is used both to supply the heat for evaporation and to carry away the evaporated moisture from the product. One of the main aims of convective drying is to achieve a proper reduction of water activity in the product; such a reduction promotes food preservation (Vásquez-Parra et al., 2013; Law et al., 2014), by avoiding microbial growth and chemical reactions causing deterioration. Most spore-forming organisms (e.g., Bacillus species) do indeed not grow at water activity values smaller than a threshold, usually equal to 0.93 (Valdramidis et al., 2006). Several different approaches were proposed to model food convective drying. The models available in the open literature may be roughly subdivided in two categories: simplified and complex approaches. Regarding the so-called simplified approaches available in the literature, some authors proposed to take into account the moisture transport only, which was described by the already-known solution of Fick's second law of diffusion, expressed in terms of an effective diffusion coefficient of water in food (Chin et al., 2009; Bon et al., 2007). Other authors, instead, accounted for the simultaneous transfer of heat and moisture in an isotropic food with no internal sources of moisture (Zuniga et al., 2007; Rahman et al., 2007). Such simplified approaches, due to a certain level of inaccuracy, however, could not be applicable to several situations of physical significance. In order to obtain a comprehensive insight about convective food drying, it is essential to formulate more detailed and general multiphase transport models, which allow developing reliable simulation tools capable of predicting the actual influence of operating conditions either on dried foods characteristics or on process performance. However, the formulation of such theoretical models often represents a rather challenging task. Solid foods, in fact, have to be regarded as hygroscopic porous media containing, besides unbound water, also a significant amount of bound water. Actually, both of them are to be removed in order to achieve the desired final moisture content. Bound water, which exerts a vapor pressure less than that of liquid water at the same temperature, is removed by progressive vaporization within the solid matrix, followed by

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diffusion and pressure driven transport of water vapor through the solid (Datta, 2007a). A simultaneous transfer of heat and mass, in the form of liquid water and vapor, takes place so that heat is transported from air to the material, whereas water is transported from the food core to its exposed surface, and, eventually, to drying air (Chua et al., 2002). In addition, the rates of heat and mass transfer at food–air interfaces are strongly affected by the velocity field of drying air flowing around the food sample(s) (Ateeque et al., 2014). An exhaustive analysis of all the complex transport phenomena involved in the food drying process was regarded in the past as too onerous and time consuming for practical purposes. However, over the last decade, a certain number of researchers have proposed interesting and innovative contributions to the literature in the field. Datta's research group formulated several comprehensive and general multiphysics models predicting heat and mass transfer rates occurring during food drying (Ni et al., 1999; Zhang and Datta, 2004; Datta, 2007a; Dhall and Datta, 2011; Halder and Datta, 2012; Gulati and Datta, 2013). In these papers, the transport phenomena occurring at food/air interfaces were described in terms of heat and mass transfer coefficients estimated from semi-empirical correlations and referred to samples having a constant characteristic dimension. When food shape is not regular, the exploitation of literature correlations might significantly limit model accuracy (Bernstein and Noreña, 2014), thus providing unreliable predictions of the actual system behavior. The transport phenomena occurring in the air and the complex fluid–structure interactions are to be properly accounted for, since they significantly affect the interfacial heat and mass transfer rates and, therefore, the overall process performance. Curcio et al. (2008) formulated a conjugated transport model describing food convective drying without resorting to any empirical transport coefficient. In a subsequent paper, Curcio (2010) improved the predictions of the previous model and simulated drying behavior when inner evaporation could not be neglected; a multiphase approach, based on the conservation of both liquid water and vapor, was formulated. Marra et al. (2010) proposed a full conjugated approach to describe the combining effects of different heating mechanisms (convective and MWs) on food drying rates.

The greatest part of the papers dealing with 3D modeling of food convective drying took into account a single sample, whose shape was referable to one of the conventional geometries, namely parallelepiped cylinder or sphere. In such cases, the semi-empirical correlations available in the literature were exploited to estimate the heat and mass transfer coefficient at food–air interfaces and, therefore, to calculate food drying rate (Bennamoun et al., 2015; Lemus-Mondaca et al., 2013). Drying modeling of a single irregular-shaped food was performed as well; however, simplified approaches, based on the definition of a geometrical shape factor, which allowed approximating the behavior of any irregular-shaped 3D object to that of an ellipsoid, were proposed (Sahin and Dincer, 2003; 2005). In other papers, the dependence of process variables on the third spatial dimension was, instead, completely neglected accounting for some symmetry conditions; the analysis, therefore, was restricted to much-simpler-to-simulate 2D geometries.

The present paper proposes a general and versatile multiphase transport model, which permits solving a problem of major interest in industry, namely the reliable evaluation of the actual mutual interactions occurring when various food samples, having generic and irregular shapes and different initial characteristics, are dried under a wide range of operating conditions. The present model does indeed precisely account for the actual shape of each of samples exposed surfaces, thus allowing calculating the time evolution of the local values of food moisture content and temperature, and their dependence on relative humidity and temperature of drying air.

2. Theory

The most significant novelty of the proposed approach is represented by the possibility of identifying, on food samples surfaces, the points where the local values of both water activity and temperature might determine an inefficient and unsatisfactory reduction of microbial spoilage probability. This is achieved by a conjugated multiphase transport model, which predicts the actual drying rates of 3D irregular-shaped foods exposed to drying air flowing around the samples. The formulated model is, therefore, capable of predicting the proper set of operating conditions, which assure that no critical areas (i.e. food portions where water activity may allow microbial spoilage) do actually exist on food surfaces. The considered foods were regarded as hygroscopic porous media, whose behavior was modeled by averaging all the variables and parameters over a representative elementary volume. Therefore, each actual multiphase porous medium was replaced by a fictitious continuum, at any point of which variables and parameters were considered as continuous functions of the spatial coordinates of the point and of time (Bear, 1972). The conservation equations describing heat transfer and the transport of liquid water, vapor and air in the porous media were combined, by a proper set of boundary conditions, to the momentum, heat and mass transport occurring in the drying air. The resulting system of non-linear unsteady PDEs was solved simultaneously by a numerical scheme based on FEM. It is worthwhile pointing out that one additional feature of the present approach is represented by the evaluation, without resorting to any semi-empirical correlation, of the heat and mass fluxes at the food/air interfaces. In the case of irregular-shaped samples, this definitely represents a significant breakthrough since the available empirical correlations, aimed at estimating heat and mass transfer coefficients at food–air interfaces, are actually valid only for specific operating conditions and for regular shaped geometries, for which a characteristic geometric dimension can be easily identified.

As compared to a previous paper published by one of the authors of the present contribution (Curcio, 2010), many simplification hypotheses were dropped out and the following improvements introduced:

a) both the considered food samples were multiphase hygroscopic porous media having generic, i.e. not referable to traditional primitives, and irregular shapes.
b) Due to the chosen dimensions, orientation and positioning of food samples in the drying chamber, no symmetry condition, which would have permitted restricting the analysis to a 2D geometry, could be invoked. Therefore, each dependent variable was actually function of the three Cartesian coordinates, x, y and z and of time, t.
c) In the porous structure of the considered food samples, three different phases, namely liquid water, vapor, and air, coexisted (Datta, 2007a); the conservation equations for each of the considered phases as well as for energy were, therefore, written.
d) The transport of liquid water within food porous structure was due to both gas pressure and capillary pressure gradients; therefore, it was not assumed, as in the previous paper, that capillary pressure contribution prevailed over gas pressure gradients.
e) In the pores of food samples, water, as vapor, was transferred by both pressure and concentration gradients; the term containing pressure driven flow was not neglected and molecular diffusion was not considered as the prevailing mechanism.
f) The conservation equation referred to air transport in food pores was taken into account, as well.

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