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Understanding forced convective drying of apple tissue: Combining neutron radiography and numerical modelling

Wondwosen Aregawi [a], Thijs Defraeye [a], Saba Saneinejad [d], Peter Vontobel [e], Eberhard Lehmann [e], Jan Carmeliet [c,d], Pieter Verboven [a], Dominique Derome [d], Bart Nicolai [a,b,*]

[a] MeBioS, Department of Biosystems, University of Leuven, Willem de Croylaan 42, 3001 Heverlee, Belgium
[b] VCBT, Flanders Centre of Postharvest Technology, Willem de Croylaan 42, 3001 Heverlee, Belgium
[c] Chair of Building Physics, Swiss Federal Institute of Technology Zurich (ETHZ), Wolfgang-Pauli-Strasse 15, 8093 Zürich, Switzerland
[d] Laboratory for Building Science and Technology, Swiss Federal Laboratories for Materials Testing and 12 Research (Empa), Überlandstrasse 129, 8600 Dübendorf, Switzerland
[e] Spallation Neutron Source Division ASQ, Paul Scherrer Institute (PSI), 5234 Villigen, Switzerland

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ABSTRACT

A multiphysics model for biological materials, coupling nonlinear viscoelastic deformation to water transport, was used to study forced convective drying of apple tissue samples (cv. Maigold). The accuracy of the model was verified with quantitative neutron radiography experiments, by comparing the total water loss, the transient water distribution profiles and the mechanical deformation. Both model simulations and experiments showed that the largest moisture gradients occurred at the air–tissue interface. The corresponding shrinkage behaviour was similar. Furthermore, the difference between simulation results from modelling the water exchange with the environment using a constant mass transfer coefficient or a spatially varying transfer coefficient from a flat-plate correlation was not significant, indicating that the drying kinetics were dominated by the water transport in the tissue rather than by the convective flow at air–tissue interface. The simulated results showed a satisfactory agreement with experimental observations. The validated model is clearly appropriate to be employed for optimization of convective drying processes of food.

Industrial Relevance: The paper adds a significant progress to the study the dynamics of drying (water transport and shrinkage) during dehydration of fruit tissue.

1. Introduction

Food drying is widely used for food preservation by inhibiting the growth of micro-organisms. It extends shelf life and minimizes packing, storage and transportation cost (Fernandes, Rodrigues, Law, & Mujumdar, 2011; Marquez & De Michelis, 2011; Mujumdar, 2006; Mujumdar & Law, 2010). Dried fruits have also been considered as alternative fat-free snacks by consumers (Devahastin & Niamnuy, 2010; Nimmol, Devahastin, Swasdisevi, & Soponronnarit, 2007; Prachayawarakorn, Tia, Plyto, & Soponronnarit, 2008). Drying is a rather slow and energy intensive process. Optimisation of drying processes is required to enhance product quality, increase processing efficiency and reduce energy consumption. For this purpose, both mathematical models and experimental methods can be applied (Veraverbeke, Verboven, Van Oostveldt, & Nicolai, 2003b; Nguyen, Verboven, Scheerlinck, Vandewalle, & Nicolai, 2006; Nguyen, Verboven, Schenk, & Nicolai, 2007; De Temmerman, Verboven, Delcour, Nicolai, & Ramon, 2008; Defraeye, Blocken, Derome, Nicolai, & Carmeliet, 2012).

On the experimental side, MRI has already been used to study drying of foods (Hills & Remigereau, 1997; Verstreken, Van Hecke, Scheerlinck, De Baerdemaeker, & Nicolai, 1998; Schrader & Litchfield, 2007; Ghosh, Jayas, Smith, Gruwel, & White, 2008; Rakesh, Seo, Datta, Mccarthy, & Mccarthy, 2010; Jin et al., 2011). X-ray (micro-) radiography and tomography studies have also been reported in the past for food drying (Aregawi et al., 2013; Leonard, Blacher, Marchot, Pirard, & Crine, 2004, 2005; Leonard, Blacher, Nimmol, & Devahastin, 2008). With this technique, a high spatial resolution can be obtained (e.g., Verboven et al., 2008). However, X-ray radiation can have a damaging effect on the tissue structure of biological materials for long exposure or high beam intensities. With MRI, but especially with X-ray, quantification of the water content is often not straightforward. Neutron imaging is an alternative technique and has already been applied to study water transport in several biological materials, namely for root growth (Esser, Carminati, Vontobel, Lehmann, & Oswald, 2010; Menon et al., 2007), for monitoring water distribution and/or transport in flowers (Matsushima et al., 2009; Nakanishi, Furukawa, & Matsubayashi, 1999), leaves (Matsushima, Kawabata, Hino, Geltenbort, & Nicolai, 2005), wood (Sedighi-Gilani et al., 2012) and fruit (Aregawi et al., 2013; Balasko, Koröusi, & Farkas, 2002; Defraeye et al., 2013). Neutron imaging was found to be particularly successful in quantifying

* Corresponding author at: MeBioS, KU Leuven, Willem de Croylaan 42, B-3001 Leuven, Belgium. Tel.: +32 16 322375.
E-mail address: bart.nicolai@biw.kuleuven.be (B. Nicolai).

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water content, but access to facilities which produce neutrons is limited.

Numerical simulations have specific advantages, compared to experiments, amongst others that they provide high spatial resolution information on both the internal temperature and moisture content distribution during drying; and that the impact of biological variability between individual samples which is inherently present in experiments, i.e. every sample is different, is avoided. The latter allows a more straightforward characterization of the influence of process parameters on the drying process. Ideally, such numerical models should include heat and water transport, combined with mechanics to account for deformations and changes in tissue properties (e.g., hardening of the outer fruit shell). As all these processes are essentially coupled, they should also be modelled accordingly.

The continuum approach is commonly used to model heat and water transport in foods, such as fruit, amongst others since it avoids the necessity of modelling the microscopic pore space (Datta, 2002; Mulligan & Reddy, 1987). In this approach, the fruit tissue is considered as homogeneous and heat and water transport modelling is based on the lumped properties of the tissue. Such models for fruit tissue are typically based on Fick's second law (Veraverbeke, Verboven, Van Oostveldt, & Nicolai, 2003a; Nguyen, Verboven, Scheerlinck, Vandewalle, & Nicolai, 2006; Kaya, Aydin, & Dincer, 2006). With respect to modelling mechanical deformation, biological materials such as fruit behave like a nonlinear viscoelastic continuum according to Wineman (2009), as fruit tissue can exhibit large deformations as a result of hygrostresses during dehydration (e.g., Aregawi et al., 2012). The nonlinear viscoelastic parameters of fruit tissue and the heat and water transport properties are mostly determined based on experiments in the continuum approach (e.g., Aregawi et al., 2012).

The majority of the existing studies on coupled water transport and deformation (shrinkage) during convective drying of food materials are either based on the assumption that the volume change due to shrinkage of the tissue is equivalent to the volume of water removed from the material (Gekas & Sjoholm, 1995; Mayor & Sereno, 2004; Piotr & Ewa, 2004; Janjai et al., 2008a,b) or calculate the deformation based on linear elasticity theory (Inazu, Iwasaki, & Furuta, 2005; Kowalski, 2005; Niamnuy, Devahastin, Soponronnarit, & VijayaRaghavan, 2008). The coupling of water transport with large deformations, based on non-linear (visco-)elastic behaviour of the fruit tissue has received much less attention. This approach has already been applied for microwave puffing (Rakesh & Datta, 2011) and apple tissue (Aregawi et al., 2013, 2012), but also for other materials such as for swelling of polymer networks (Duda et al., 2010) and elastomeric materials (Anand & Chester, 2010).

The objective of this study was to investigate effects of external convective flow on the apple tissue drying process, including aspects such as drying kinetics and the spatial distribution of the water and mechanical deformation (shrinkage) during forced convective drying. To achieve this, a multiphysics model, which couples water transport with mechanical deformation and interface coupling of water transport at the surface of food, was applied. Furthermore, a dedicated forced convection setup was built and used for quantitative neutron radiography to investigate the process experimentally and verify the model results.

2. Materials and methods

2.1. Neutron experiment

2.1.1. Material

For the neutron experiment, the apple was (cv. Maigold) bought in a local grocery shop (Villigen, Switzerland) the day before the actual experiment. The neutron experiment was performed on May 12th–13th 2011, using a rectangular fruit sample (length × height × width (x,y, z) ~ 40 × 30 × 10 mm), which was cut from fresh fruit right before the experiment.

2.1.2. Convective drying experiment by neutron radiography

These experiments were performed by Defraeye et al. (2013), where a detailed description can be found. The basic characteristics of the experiments are repeated briefly below. An open-circuit wind-tunnel setup, shown in Fig. 1, was used to study convective drying of apple fruit sample with neutron imaging, which allowed analysis of water distribution and mechanical deformation. After cutting the rectangular sample, it was thermally insulated (with XPS) and was made impermeable for water on all surfaces (i.e., by wrapping it in aluminium foil), except for the surface interfacing the channel flow (see Fig. 3). The x–y plane was placed perpendicular to the neutron beam. A tangentially cut rectangular apple tissue sample was used for experiment (Fig. 3). Note that there are differences in orientation of cells in the radial and longitudinal direction of apple tissue, by which the orientation of the sample could affect the dehydration behaviour (Abbott & Lu, 1996). In this study, we did not consider different tissue orientations due limited beamtime in the neutron facility.

The imaging facilities of the Neutron Transmission Radiography beamline (NEUTRA) at the Paul Scherrer Institute (PSI, Villigen, Switzerland) were used for detailed visualization and quantification of transient water transport in apple tissue. Fig. 2 shows a schematic overview of the neutron beamline with the test setup. The field of view was 85 × 85 mm^2, and with a 2048 × 2048 pixel CCD camera, a spatial resolution of 83 μm was obtained.

Neutron imaging is particularly suitable for quantifying water content in biological materials due to its high sensitivity to hydrogen. The water content can be determined from the intensity of the transmitted polychromatic beam (I) as follows. This intensity at a specific time (t) can be described with the Beer–Lambert law:

$$I(t) = I_0 \exp[-(\mu_{dm} z_{dm} + \mu_{TS} z_{TS} + \mu_w z_w(t))] \quad (1)$$

where I_0 is the intensity of the incident neutron beam, the subscript dm refers to the (dry) fruit tissue, TS to the wind-tunnel test setup and w to the water (liquid and vapour), μ_{dm} is the effective attenuation coefficient of dry fruit for neutrons (m^{-1}), z_{dm} is the thickness of dry matter (m), μ_{TS} is the effective attenuation coefficient of test setup for neutrons (m^{-1}), z_{TS} is the thickness of test setup (m), μ_w is the effective attenuation coefficient of water for neutrons (m^{-1}) and z_w is the thickness of water (m). Assuming fruit tissue shrinkage in the direction along the neutron beam had a negligible effect on beam attenuation, Eq. (1) can be written as:

$$I(t) = I_0 \exp[-(\mu_{dm} z_{dm} + \mu_{TS} z_{TS} + \mu_w (z_w(t_0) + \Delta z_w(t)))] \quad (2)$$

where t_0 is the time of the first neutron image after the start of the drying experiment, $z_w(t_0)$ is the initial water thickness, $\Delta z_w(t)$ is the reduction in water thickness at time t due to the water removal from the sample during drying. Assuming that the change in neutron beam attenuation in the drying experiment is due to a change in water content in the sample, the change in water thickness ($\Delta z_w(t)$) can be solved based on Eq. (2):

$$\Delta z_w(t) = -\frac{1}{\mu_w} \ln\left(\frac{I(t)}{I(t_{ini})}\right) \quad (3)$$

with $I(t_{ini}) = I_0 \exp[-(\mu_{dm} z_{dm} + \mu_{TS} z_{TS} + \mu_w(z_w(t_0)))]$where $I(t_{ini})$ is the intensity of the neutron beam leaving the initial, freshly cut fruit sample, i.e., at the start of the neutron experiments.

Multiplying this reduction in water thickness with the density of water ρ_w (kg m^{-3}) and dividing by the total (initial) specimen thickness ($z_{tot,ini} = z_{w,ini} + z_{dm,ini}$) and dry matter density ρ_{dm} (kg$_{\mathrm{dm}}$ m^{-3}) give the change in dry base water content of the sample over time $\Delta X_W^{db}(t)$ (kg kg$_{\mathrm{dm}}^{-1}$):

$$\Delta X_W^{db}(t) = \rho_w \frac{\Delta z_w(t)}{\rho_{dm} z_{tot,ini}} = -\frac{\rho_w}{\rho_{dm} \mu_w z_{tot,ini}} \ln\left(\frac{I(t)}{I(t_{ini})}\right) \quad (4)$$

$$X_W^{db}(t) = X_W^{db,ini} + \Delta X_W^{db}(t) \quad (5)$$