Journal of Food Engineering 178 (2016) 198–202

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Probing inside fruit slices during convective drying by quantitative neutron imaging

Thijs Defraeye [a, b, c, *], Bart Nicolaï [c, d], David Mannes [e], Wondwosen Aregawi [c], Pieter Verboven [c], Dominique Derome [a]

[a] Multiscale Studies in Building Physics, Empa, Überlandstrasse 129, 8600 Dübendorf, Switzerland
[b] Chair of Building Physics, Swiss Federal Institute of Technology Zurich (ETHZ), Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland
[c] MeBioS, Department of Biosystems, University of Leuven, Willem de Croylaan 42, 3001 Heverlee, Belgium
[d] VCBT, Flanders Centre of Postharvest Technology, Willem de Croylaan 42, 3001 Heverlee, Belgium
[e] Paul Scherrer Institute (PSI), 5234 Villigen, Switzerland

ARTICLE INFO

Article history:
Received 28 August 2015
Received in revised form
11 December 2015
Accepted 24 January 2016
Available online 26 January 2016

Keywords:
Non-destructive imaging
Apple
Convective
Drying
Tunnel
Dehydration

ABSTRACT

Quantitative neutron imaging was applied for the dynamic monitoring of the internal moisture distribution of fruit slices during convective drying in a drying tunnel. The impact of several process conditions was evaluated, including airflow temperature, air speed and incident radiation. This technique also unveiled that anisotropic shrinkage was caused, in part, by spatially heterogeneous dehydration, as induced by the presence of the peel. Neutron imaging provided unique graphical and quantitative insights on how the internal water distribution evolved. Thereby, this imaging technique has large potential to complement conventional techniques for monitoring, controlling and optimising drying processes of complex biomaterials, or to generate high-resolution validation data for numerical simulations.

1. Introduction

Drying is one of the most important thermal processing operations for preserving fresh fruits and vegetables (Dev and Raghavan, 2012). The resulting extended shelf life and prolonged storage capability guarantee off-season availability of this source of nutrition and also help in reducing food waste. These aspects are critical in developing countries, which often rely on solar energy to dry fruit due to the limited access to conventional energy sources. In developed countries, dried fruits are gaining popularity as healthy snacks, for example apple chips or fruit leathers. Efforts towards enhancing drying processes of such products and the resulting product quality are therefore on the rise (Defraeye, 2014). Both low-tech solutions for rural application, such as solar-assisted dryers, as well as high-tech industrial implementations are targeted. The latter mainly aim at reducing energy consumption and delivering a uniform product quality, which is extremely challenging for complex biomaterials such as fruits.

Next to the recent computational modelling efforts on fruit and vegetable drying (Halder and Datta, 2012; Marra et al., 2010), a large amount of experimental work was performed (Santacatalina et al., 2014; Sturm et al., 2012). Most of these experiments however target the overall drying kinetics and final product quality but do not probe the moisture transport inside the fruit during drying. Internal water transport is however decisive for the moisture content and its distribution within the fruit after drying, the product's final microstructure, the sorption and rehydration behaviour, and the degree of case hardening. Opportunely, non-destructive imaging provides ways of dynamically monitoring water distribution during drying (Nicolaï et al., 2014).

The most commonly-used imaging techniques that have been applied for fruit drying are nuclear magnetic resonance (NMR, Van As and van Duynhoven, 2013), X-ray radiography/tomography (Léonard et al., 2008) and neutron radiography/tomography

---

* Corresponding author. Multiscale Studies in Building Physics, Empa, Überlandstrasse 129, 8600 Dübendorf, Switzerland.
E-mail addresses: defraeye@arch.ethz.ch, thijs.defraeye@empa.ch (T. Defraeye).

http://dx.doi.org/10.1016/j.jfoodeng.2016.01.023

(Aregawi et al., 2013; Defraeye et al., 2012a). They differ with respect to their spatial and temporal resolution, their capability to detect water qualitatively (dynamic range, i.e. the number of contrast levels) and quantitatively (absolute water content), their accessibility and their ease of use (Defraeye et al., 2012a). Neutron imaging has some particular advantages. It provides a very high dynamic range since the neutron beam is attenuated strongly by hydrogen, thus water. In addition, a straightforward correction procedure exists (Hassanein et al., 2005), by which accurate water content distributions can easily be obtained from the neutron radiographs, which is so-called quantitative neutron imaging. Combined with its spatial and temporal resolution (typically ~10^1–10^2 μm and ~10 s for a radiograph), this technique is particularly suitable for monitoring and analysing internal water transport and water loss during drying of whole, fresh-cut fruit slices in a non-intrusive way. Only a few studies have been reported for this application, but they had a rather limited quantitative appraisal (Balasko et al., 2002) or aimed at evaluating the accuracy of the technique for academic cases, which had limited similarity with actual convective drying applications (Aregawi et al., 2013; Defraeye et al., 2012a). A downside of neutron imaging is the limited number of dedicated beamlines available, but the situation is rapidly improving (Lehmann and Ridikas, 2014).

This study probes the water distribution changes in apple fruit slices during forced convective drying by quantitative neutron imaging. The specific aim is to take new steps in this field, namely by considering a realistic turbulent airflow field around the fruit in a drying tunnel, and by targeting the impact of several process conditions (airflow temperature, air speed and incident radiation), and the presence of the fruit peel.

2. Materials and methods

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 fruit tissue. The experimental characteristics for imaging are: a CCD camera with 2048 × 2048 pixels, a pixel resolution of 100 μm and an exposure time per radiograph of 13 s.

An open-circuit, custom-built, aluminium wind tunnel (Lal et al., n.d.) was used to subject fruit samples to controlled airflow conditions while imaging their internal water content distribution with neutron radiography. The channel test section was 316 × 50 × 105 mm (length × height × width, x–y–z). Two airflow rates were evaluated in this study, leading to average air speeds in the test section of 1.1 and 2.6 m s^{-1} (U_{avg}). These speeds correspond to Reynolds numbers (Re) of 3700–9000 (based on U_{avg} and channel height H), which implies turbulent flow. The temperature of the approach flow (T_{AF}) was actively controlled, which thereby also affected the relative humidity (RH_{AF}, not controlled but rather low due to the specific environmental conditions in the neutron facility). Several experiments were performed, of which the details are given in Table 1. In some experiments, irradiation onto the fruit surface was added by means of a lamp (Osram "Ultra-Vitalux", 300 W). This lamp was placed at an oblique angle above the transparent, glass test section roof (45°), at 30 cm distance from the fruit sample. For one experiment (Ex7), only natural convection was induced, driven by irradiation, instead of forced convection.

Apple fruits (cv. *Braeburn*) were used. Half-circular apple slices of about 1 cm thick were cut along the centre axis of the fruit (axis from petiole to crown, see Fig. 1). With one sample (Ex4), the peel was removed. Each sample was suspended on two needles in the centre (x–y–z) of the test section, after which the drying process was started. Each experiment took around 8–10 h, during which neutron radiographs were acquired every minute.

The initial mass (m_{ini}) of each sample and its mass at the end of the experiment (m_{end}) were measured gravimetrically, from which the total sample water loss was determined ($\Delta m_{grav} = m_{ini}\text{-}m_{end}$). The initial water content (w_{ini}) was determined as the ratio of the total amount of water in the fruit sample (difference of initial mass (m_{ini}) and dry mass after oven drying the sample (m_{dry})) to the initial sample volume (see Table 1). This sample volume was estimated from the initial sample thickness (d_{ini}) and the frontal, cross-sectional area in the initial neutron radiograph ($A_{f,ini}$, see Fig. 1). Note that the samples were not fully dry, i.e. in equilibrium with the drying air, at the end of the experiments. This means that still an amount of moisture is present in the samples.

The neutron radiographs were corrected to obtain quantitative estimates of the water content distribution inside the sample. The applied correction procedure was developed by Hassanein et al. (2005) and is described in detail in Defraeye et al. (2012a) for fruit drying. Due to the thin aluminium walls of the test section and their transparency for neutrons, only the fruit attenuated the neutron beam. This correction procedure assumes that beam attenuation is only caused by water inside the fruit, and does not account for attenuation by the fruit tissue. This assumption was shown to give a satisfactory accuracy (Defraeye et al., 2012a) since fruits are mainly composed out of water. Note that when differences in moisture content between two images are considered, e.g. when comparing the mass loss between the initial state and a partially dried sample after a few hours, the fruit tissue contribution is cancelled out as it is present in all images. These corrections resulted in radiograph images which directly provide the water distribution for each pixel (g cm^{-2}), out of which the total water loss of the sample could be determined over time ($\Delta m_{neutr}(t)$).

3. Results and discussion

The moisture distribution inside the fruit at different times during the drying process is illustrated in Fig. 1 for four experiments: forced convection with peel, forced convection without peel, forced convective airflow combined with additional irradiation, and radiation-driven natural convection. The moisture distribution is represented dimensionless by scaling the corrected quantitative neutron radiographs (in kg m^{-2}), namely by dividing by an average slice thickness (1 cm) and by an average moisture content of fresh apple fruit (666 kg m^{-3}), after scaling all these quantities to standard units. Since the same scaling factor is used for all experiments, differences in initial moisture content are visible in Fig. 1. In addition, the mass loss from each sample over time ($\Delta m_{neutr}(t)$) was determined from the corrected neutron radiographs (Fig. 2 and Table 1). This mass loss (in g) was scaled with a surface area (in cm^{-2}) since the size of the samples differed, thus also the surface area exposed for vapour exchange. Scaling was done by dividing the mass loss with two times the initial frontal area ($A_{f,ini}$). Such scaling leads to mass loss per unit surface area (g cm^{-2}) over time, which allows better comparison between different experiments. The differences found between the mass loss from neutron imaging and that from gravimetrical measurements (Table 1) are comparable to those of Defraeye et al. (2012a). These were around 20–30% and also possible reasons for this mismatch are given there.

The images from Fig. 1 provide unique information on moisture distribution and gradients. The peel has a distinct impact on the dehydration and deformation behaviour. Without a peel, the deformation and dehydration is quasi isotropic in x and y directions. With the peel however, the fruit curls as the lower edge