Innovative Food Science and Emerging Technologies 38 (2016) 262–271

Contents lists available at ScienceDirect

Innovative Food Science and Emerging Technologies

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

Towards more efficient intermittent drying of fruit: Insights from combined hygrothermal-quality modelling

Thijs Defraeye

Multiscale Studies in Building Physics, Empa, Überlandstrasse 129, 8600 Dübendorf, Switzerland
Chair of Building Physics, ETH Zurich, Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland

ARTICLE INFO

Article history:
Received 1 June 2016
Received in revised form 26 August 2016
Accepted 5 October 2016
Available online 8 October 2016

Keywords:
Convective
Quality
Hygrothermal
Numerical simulation
Dehydration
Tempering

ABSTRACT

Intermittent drying is a promising alternative to continuous drying, as it enables moisture redistribution during tempering periods, leading to higher effective drying rates when the process is started again. This strategy can effectively reduce the net residence time in the dryer, which can help save process energy and increase product throughput. The milder temperature conditions that occur during tempering can also be beneficial for fruit quality. Intermittent drying is analyzed, in a new way, by combining hygrothermal simulations of the drying process with a temperature-dependent kinetic model for fruit quality degradation during drying. This method enabled to quantify the total process time of the fruit, the effective residence time in the dryer but also product quality degradation. By means of a parametric study, we obtained new insights in the impact of tempering time, total cycle time for drying and the ambient humidity conditions during tempering. By intermittent drying, the residence time could be reduced successfully without compromising fruit quality.

Industrial relevance: The modelling strategy provides combined information on the water activity level in the fruit and the fruit quality state during drying. This enables, in a unique way, to optimize the drying process conditions for intermittent drying in order to achieve fast drying and still obtain prime product quality. Thereby a better identification of possible savings in energy and processing time is possible for intermittent drying as well as their relation to the final quality of the fruits.

1. Introduction

As an alternative to continuous convective drying, intermittent drying can be used (Chua et al., 2003; Kumar et al., 2014; Lewicki, 2006). Intermittent drying implies that the drying process is alternated with one or more tempering periods, during which the evaporation rate from the drying product is drastically reduced. This can be achieved by controlling the air temperature, humidity, air flow rate or operating pressure, but also by altering the intensity of additional heat input sources (e.g. infrared or microwave radiation). These changes in operational conditions can be done in many ways to achieve such intermittency, for example by varying them according to step-up/step-down, sinusoidal-wave, square-wave or saw-toothed regimes (Ho et al., 2002). In most cases, only a few (2–3) tempering cycles are executed, where the heat supply by any of the different modes of heat transfer (convection, radiation, conduction) is altered to achieve intermittency. For intermittent batch drying, a temporal variation in the operating conditions is typically applied whereas for continuous processes intermittency is induced by a spatial variation of such heat input inside the dryer.

The aim of intermittent drying is that the moisture in the food redistributes during tempering, from the wet core towards the drier surface, due to the lower convective vapor removal at the surface. This evens out moisture gradients inside the product and leads to an increase in moisture content near the air-material interface. As a result from this relaxation period, the drying rate will be higher when the drying process is started again, compared to the drying rate at the point at which it was stopped during continuous drying. The reason is that more moisture is available near the fruit surface and thus the vapor pressure gradient over the boundary layer becomes larger. Thereby, intermittent drying was found to be able to reduce the effective drying time for fruits and vegetables (Chua et al., 2003; Kumar et al., 2014), i.e. the net time the product spends in the dryer. A lower total drying time could even be achieved in some cases (Ho et al., 2002). The reduced residence time in the dryer is therefore argued to increase the energy efficiency of the drying process. Furthermore, the water that migrated to the surface during tempering will make that, once the drying process is started again, evaporation occurs close to the surface rather than deep inside the fruit tissue. As a result, surface temperatures are lower by which the surface is protected more against overheating. Tempering thus leads to a “thermally-resistive layer” (Chou et al., 2000). The additional moisture will also limit the risk of overdrying at the surface, which can lead to case hardening or surface cracking due to excessive dehydration stresses. The reduced exposure to elevated temperatures also induces

http://dx.doi.org/10.1016/j.ifset.2016.10.003
1466-8564/

better product quality, as active compounds (vitamins) and color are better retained (Ho et al., 2002; Kowalski et al., 2013).

Intermittent drying can thus significantly improve product quality, energy use of the drying process and effective operational time inside the dryer. It is especially an interesting alternative for heat-sensitive materials, such as fruit, due to the milder temperature conditions it induces. It is particularly effective for materials which predominantly dry in the second drying period (decreasing drying rate period, DDRP), rather than in first drying period (constant drying rate period, CDRP). During the CDRP, the moisture transport in the material is sufficiently fast to continuously supply liquid water to the surface. In the DDRP, the transport inside the material is limiting the drying process by which a moisture redistribution after tempering will enhance the drying rate. Many fruits typically have either no, or a very short CDRP (Ateeque et al., 2014; Ben Mabrouk et al., 2012; Mcminn and Magee, 1999), so they are very suitable materials to dry intermittently. It makes even only sense to start intermittent drying once the CDRP has passed (Kowalski et al., 2013). Despite the advantages, particularly for heat-sensitive biomaterials or pharmaceuticals, rather limited research has been performed on intermittent drying compared to other drying technologies. As such, it is still considered to be a quite novel technique (Kumar et al., 2014), although being introduced already some time ago.

Next to simple analytical or semi-empirical models (Baini and Langrish, 2007; Nishiyama et al., 2006), continuum modelling is an interesting alternative to experiments to analyze intermittent drying (Baini and Langrish, 2007; Ben Mabrouk et al., 2012; Chou et al., 2000; Ho et al., 2002; Putranto and Chen, 2013; Váquiro et al., 2009). Its main advantages are that, next to overall moisture loss, also the internal moisture distribution, temperature and water activity can be tracked throughout the entire drying process. Both surface-averaged and volume-averaged quantities can be extracted. Furthermore extensive parametric evaluations can be performed in relatively short timeframes, without being inherently hindered by experimental or biological uncertainty.

The numerical studies for intermittent fruit drying are however quite scarce (Kumar et al., 2014), and several aspects received little attention. The environmental conditions during tempering, especially the humidity, were often not specified or taken into consideration as a key parameter (Kumar et al., 2014). However, humidity and temperature during tempering are essential to quantify the moisture loss or uptake of the tissue to the environment, thus the moisture redistribution kinetics. In some studies, the impact of the environmental conditions during tempering was bypassed by restricting moisture removal (Barbosa de Lima et al., 2016; Nishiyama et al., 2006). Such a zero-flux condition can be enforced in laboratory experiments, by wrapping the fruit inside a plastic foil, but is less straightforward on an industrial scale. Furthermore, previous studies did focus on moisture loss and drying rates but not on the internal moisture redistribution kinetics during tempering (Kumar et al., 2014).

We aim to gain more insight particularly on these aspects of intermittent drying of fruit. To this end, a parametric study is performed for this heat-sensitive biomaterial, evaluating (1) tempering time; (2) total cycle time; and (3) ambient humidity conditions during tempering. We assess the impact of these parameters by quantifying the total process time of the fruit, the effective residence time in the dryer but also product quality degradation, based on the simulated fruit temperature history. This systematic study leads to better identification of possible savings in processing time and energy for intermittent drying and their relation to the final quality of the fruits.

2. Materials and methods

2.1. Continuum model for fruit tissue

A continuum model was developed previously (Defraeye and Verboven, 2016) for calculating the heat and moisture transfer in fruit tissue during drying. The model validation is also presented in that work. Only its main characteristics are highlighted below and more details can be found elsewhere (Defraeye and Verboven, 2016). The main model assumptions are that evaporation is assumed to occur only at the tissue surface and that shrinking and swelling of the tissue are not modelled, which is often assumed in multiphysics modelling of fruit drying (Thijs Defraeye, 2014).

2.1.1. Conservation equations

The following conservation equations for moisture and energy are solved to the dependent variables temperature T [K] and water potential ψ [Pa]:

$$\frac{\partial w_m}{\partial \psi}\frac{\partial \psi}{\partial t} + \nabla \cdot (-K_m \nabla \psi) = 0 \quad (1)$$

$$h_l \frac{\partial w_m}{\partial \psi}\frac{\partial \psi}{\partial t} + (c_{p,s} w_s + c_{p,l} w_m)\frac{\partial T}{\partial t} + \nabla \cdot (-h_l K_m \nabla \psi) + \nabla \cdot (-\lambda_{PM} \nabla T) = 0 \quad (2)$$

where w_s and w_m are the dry matter density (solid) [kg m^{-3}] and moisture content of the tissue [kg m^{-3}], respectively. K_m is the moisture permeability of the tissue [s], h_l is the enthalpy of liquid water [J kg^{-1}], λ_{PM} is the thermal conductivity of the tissue (porous medium) [W m^{-1} K^{-1}], $c_{p,s}$ and $c_{p,l}$ are the specific heat capacities of dry matter and liquid water [J kg^{-1} K^{-1}], respectively. These material properties are given in Table 1. K_m and the sorption isotherm are taken from (Aregawi et al., 2013). In the energy conservation equation, the impact of the first and third term is actually very small in the present study due to the low drying rates. These terms are not accounted for in many studies.

2.1.2. Boundary conditions

The boundary conditions at the air-tissue interface (continuity of fluxes) are specified as:

$$\boldsymbol{n} \cdot (-K_m \nabla \psi) = g_m = h_{c,m}\left(p_{v,w} - p_{v,ref}\right) \quad (3)$$

$$\boldsymbol{n} \cdot (-h_l K_m \nabla \psi - \lambda_{PM} \nabla T) = g_T = \left(h_{c,T}(T_w - T_{ref}) - h_v g_m\right) \quad (4)$$

where g_m [kg m^{-2} s^{-1}] and g_T [J m^{-2} s^{-1}] are the mass and heat fluxes at the interface, **n** is the unit vector normal to the interface, $h_{c,m}$ is the convective mass transfer coefficient (CMTC [s m^{-1}]), $h_{c,T}$ is the convective heat transfer coefficient (CHTC [W m^{-2} K^{-1}]), $p_{v,w}$ and $p_{v,ref}$ are the vapor pressures at the interface and of the ambient air [Pa], T_w and T_{ref} are the temperatures at the interface and of the ambient air [K], h_v and h_l are the enthalpies of water vapor and liquid water [J kg^{-1}], respectively.

For heat transfer, the boundary condition states that heat loss from the tissue, due to conduction and liquid water transport, equals the convective (sensible) heat exchange with the environment and the heat removal due to the water vapor loss, including evaporation. For mass transfer, the boundary condition states that the moisture loss from the tissue equals the convective vapor removal from the surface. In the present study, long-wave radiation exchange of the tissue with the environment via the surface was not included in the modelling.

2.1.3. Constitutive equations

The enthalpies of water vapor and liquid water, h_v and h_l [J kg^{-1}], are:

$$h_l = c_{p,l}(T - T_{ref,0}) \quad (5)$$

$$h_v = c_{p,v}(T - T_{ref,0}) + L_v \quad (6)$$

where L_v is the heat of vaporization [J kg^{-1}], also called latent heat,