Convective drying of fruit: a deeper look at the air-material interface by conjugate modeling

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ABSTRACT

A better physical understanding but also prediction of convective drying processes of fruit is essential for further process optimization. This study uses validated conjugate modeling to gain insight in how fruit drying kinetics are related to the convective heat and mass exchange with the surrounding turbulent airflow via the fruit surface. Conjugate modeling implies that the heat and mass transport in both air and fruit domains are solved simultaneously. We explore the impact of several model assumptions and different convective drying conditions. The conjugate model is inherently more accurate than the use of constant convective transfer coefficients (CTCs), so the non-conjugate approach. However the gain in accuracy was found to be limited in terms of overall fruit drying kinetics, such as total mass loss. Nevertheless, conjugate modeling allowed to identify spatial and temporal variability in CTCs, which locally affected drying rates and internal moisture content distribution. Thereby, we identified the occurrence of negative convective transfer coefficients, which led to rehydration at specific locations on the fruit surface, due to the surrounding high-humidity microclimate. The ability to identify the direct relation between non-uniformities in the airflow to those in the tissue is a unique trait of the conjugate approach. Furthermore, it was shown that isothermal modeling should not be used, even for near-isothermal conditions such as low-temperature drying, and that including thermal radiation exchange with the environment clearly affected the drying rates. Regarding the drying conditions, the impact of the air speed and approach flow temperature was found to be smaller compared to altering the approach flow humidity. When direct solar radiation was present, the presence of airflow provided significant cooling of the fruit, which is beneficial for preserving heat-sensitive nutritional compounds in the fruit, and also enhanced the drying rate. This study will aid drying technologists to define the required complexity of their model.

Keywords: conjugate; apple; solar; dehydration; boundary layer; radiation; convection

1. INTRODUCTION

Convective drying is an important unit operation to process food material and to preserve highly-perishable foods, such as fresh produce (Defraeye, 2014; Mujumdar, 2014). Nowadays, drying processes are particularly optimized towards improving the homogeneity in quality between individual products and reducing the energy consumption of the process, due to the energy-intensive nature of moisture removal. Next to industrial processes, rural applications of drying of fresh fruit and vegetables increased tremendously over the past years. Typical examples are solar-assisted drying (Bal et al., 2010; Belessiotis and Delyannis, 2011; El-Sebaei and Shalaby, 2012; VijayaVenkataRaman et al., 2012) or solar pervaporation (Phinney et al., 2015) as strategies to mitigate food waste. Solar power is not only a convenient way of saving process energy but also enables drying in regions where access to conventional energy sources is scarce.

A better physical understanding but also prediction of convective drying processes of food products is essential for further process optimization. Currently, we still lack insight in how fruit drying kinetics are related to the convective heat and mass exchange with the surrounding turbulent airflow via the boundary layer, and to the thermal and solar radiation exchange with the environment. As a result, the impact of more complex operational and environmental conditions on the drying kinetics, the internal moisture distribution and food quality has been often left unexplored. Typical examples of such complex convective drying processes are intermittent drying (Kumar et al., 2014) and solar-assisted drying (Murthy, 2009), where the latter is subject to fluctuations in incident radiation from the day-night cycle and the presence of clouds. Both processes induce partial rehydration of the material and moisture redistribution inside the fruit during relaxation periods, due to the lower drying rates. Gaining more insight in the exchange processes at the air-fruit interface is a key step towards better understanding and improving convective drying processes. Also in other research fields, insights in the heat and mass exchange of porous materials with the turbulent airflow are of particular interest (Aminzadeh and Or, 2013; Defraeye et al., 2014, 2013a; Haghighi and Or, 2013; Shahraeeni et al., 2012).

Although experiments on fruit drying (Vega-Gálvez et al., 2012; Velić et al., 2004; Zlatanović et al., 2013) can be used to answer some questions, they do not provide the same level of detail as numerical models. Simulations typically target heat and mass transport within the product, and are often solved using finite element modeling (FEM). These models have recently been coupled to the transport in the surrounding airflow as well, so called conjugate modeling (Caccavale et al., 2015; Defraeye, 2014). Such conjugate simulations provide all process parameters (temperature, moisture content, etc.) within the product, in the surroundings and at their interface at very high spatial and temporal resolution. Even scales or locations which are difficult to access experimentally can be targeted. Also the sensitivity to small changes, such as drying conditions, is clearly detected as no “experimental uncertainty” or problems with repeatability are present. Such information leads to a deeper physical insight and understanding of the dehydration kinetics, which can feed new ideas for (re)designing or optimizing drying processes. The current

conjugate models for fruit or vegetable drying (e.g. (Curcio et al., 2015; Halder and Datta, 2012; Kurnia et al., 2013; Lamnatou et al., 2010, 2009; Marra et al., 2010)) however did not focus on a few key aspects in detail.

First, the convective process is mainly targeted, by which thermal (long-wave) and solar radiation exchange are rarely included in the models. Second, wall functions are preferred to model the convective boundary layer, instead of low-Reynolds number modeling (LRNM). Wall functions avoid resolving the boundary layer explicitly in order to reduce the computational costs and to facilitate grid generation. They however often lead to inaccurate predictions, especially for wall friction and convective heat transfer (Allegrini et al., 2012; Defraeye et al., 2013b, 2010). Third, the conjugate model is assumed to be inherently more accurate, but the gain in accuracy with the non-conjugate approach, which just uses convective heat and mass transfer coefficients to account for the convective exchange, is not quantified. Fourth, often square or rectangular geometries are used.

In this study, validated conjugate modeling will be used to shed light on the aforementioned aspects for the case of turbulent convective drying of a half-circular fruit slice. On one hand, the focus is on the physics of the drying process, particularly on the heat and mass exchange between fruit and turbulent airflow at their interface, including the effect of thermal and solar radiation. On the other hand, the conjugate model is used to explore the impact of several model assumptions or limitations of previous models on the drying process. We also identify the need for applying a conjugate approach over a non-conjugate one. Apple fruit is chosen as it is often used to study drying of fresh produce and since it has a significant economic relevance.

2. MATERIALS AND METHODS

2.1 Conjugate model

A continuum model is developed to calculate heat and moisture transport in fruit tissue and in the surrounding air during drying. It is based on a previously developed conjugate model ((Defraeye et al., 2012a) based on (Janssen et al., 2007)), but adjustments are made to the porous medium model to account for the case of apple fruit drying (see (Defraeye and Verboven, 2016)). The conjugate model is also extended to account for turbulent, instead of laminar, airflow and for thermal and solar radiation exchange at the air-tissue interface. The main model characteristics are highlighted here but details can be found in (Defraeye et al., 2012a; Defraeye and Verboven, 2016).

Porous medium model

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

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

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

where w_s and w_m are the dry matter content (solid) 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 (moist porous medium, so including water) [$\text{W m}^{-1} \text{K}^{-1}$], $c_{p,s}$ and $c_{p,l}$ are the specific heat capacities of dry matter and liquid water [$\text{J kg}^{-1} \text{K}^{-1}$], respectively. These material properties are given in Table 1. K_m and the sorption isotherm were determined earlier (Aregawi et al., 2013a). Note that the first term of Eq.(1) is the moisture capacity

$$C_m = \frac{\partial w_m}{\partial \psi}, \text{ which is further detailed below.}$$

Note that moisture transport is not split up in vapor and liquid water transport, leading to only one conservation equation. No air transport in the fruit is modeled. The main model assumptions are that: (1) evaporation is assumed to occur only at the surface, implying that moisture transport in the fruit tissue occurs via the liquid phase and not via water vapor, (2) shrinking and swelling of the tissue are not modeled. Both assumptions are often assumed in multiphysics modelling of fruit drying (Defraeye, 2014). In the energy conservation equation, the impact of the first and third term is actually very low in the present study due to the low drying rates. These terms are not accounted for in many studies. Note that all fruit components (solid, liquid and vapor) are assumed to be in thermal equilibrium, which is justified due to the slow drying process. The partial differential equations Eqs.(1-2) are implemented exactly as reported here in the computational model. Note that other model implementations are also possible, for example to the dependent variables w_m (moisture content) or X (dry base moisture content). The current implementation (derived from (Defraeye et al., 2012a) based on (Janssen et al., 2007)) was found to be more numerically stable, especially if the material properties are for example dependent on moisture content.

Table 1. Material properties of fruit tissue and air for the base case.

Material properties	Symbol	Value
Moisture permeability fruit tissue	K_m	8×10^{-16} [s]
Thermal conductivity fruit tissue	λ_{PM}	0.418 [$\text{W m}^{-1} \text{K}^{-1}$]
Specific heat capacity dry matter	$c_{p,s}$	1634 [$\text{J kg}^{-1} \text{K}^{-1}$]
Specific heat capacity liquid water	$c_{p,l}$	4182 [$\text{J kg}^{-1} \text{K}^{-1}$]
Specific heat capacity water vapor	$c_{p,v}$	1880 [$\text{J kg}^{-1} \text{K}^{-1}$]
Dry matter content	w_s	130 [kg m^{-3}]
Sorption isotherm	$w_m(a_w)$	$w_s \left(\frac{0.15926}{\ln \left(\frac{1.0177}{a_w} \right)} \right)^{\frac{1}{0.97014}}$ [kg m^{-3}]
Density liquid water	ρ_l	1000 [kg m^{-3}]
Latent heat	L_v	2.5×10^6 [J kg^{-1}]
Specific gas constant for water vapor	R_v	461.52 [$\text{J kg}^{-1} \text{K}^{-1}$]

Binary diffusion coefficient of water vapor in air	D_{va}	$2.31 \times 10^{-5} \left(\frac{T}{273.16} \right)^{1.81} [\text{m}^2 \text{s}^{-1}]$
Emissivity of the fruit surface	ϵ_s	0.95
Absorption coefficient of short-wave radiation	α_s	0.5

Air flow model

Air flow is modeled by solving the general Navier-Stokes equations for turbulent flow, i.e. the conservation equations of mass (dry air and water vapor), momentum and energy by means of computational fluid dynamics (CFD). These transport equations can be found in several fluid-mechanics textbooks and are therefore not repeated here.

Turbulence is modeled by applying the Reynolds-averaged Navier-Stokes (RANS) approach in combination with the shear stress transport (SST) k- ω turbulence model. This is a modification of the standard k- ω model, proposed by (Menter, 1994). This model uses a two-equation k- ω model formulation to solve the near-wall region, for which the k- ω models were originally developed, while a k- ϵ model formulation, developed for high-Reynolds number flows, is used to solve the turbulent core region of the flow. This model can improve flow predictions with strong non-equilibrium effects and retains the k- ω model near-wall performance (Casey and Wintergerste, 2000).

This turbulence model applies a low-Reynolds number modeling (LRNM) approach to model transport in the boundary layer. The boundary layer is explicitly resolved, which requires an extremely high grid resolution for LRNM at high Reynolds numbers. This approach is much more accurate than the commonly used wall functions (Defraeye et al., 2013a, 2013b), especially for wall friction and convective heat transfer, so for conjugate problems. Wall functions are often the preferred choice as they provide advantages in terms of increased computational economy and easier grid generation. Instead of resolving the boundary layer, wall functions calculate the flow quantities in the boundary-layer region by means of semi-empirical functions.

Buoyancy effects are not taken into account in the simulations as only forced-convective flow is considered. The assumption essentially means that airflow is not driven by differences in air density caused by temperature gradients. As temperature does not influence the flow field, heat can be considered as a passive scalar. Moist air is considered to be a dilute mixture of water vapor in dry air. In addition to the general, well-known Navier-Stokes equations for mass, momentum and energy transport, following conservation equation is solved for vapor transport:

$$\frac{\partial \rho_v}{\partial t} + \nabla \cdot (-D_{va} \nabla \rho_v) + \mathbf{u} \cdot \nabla \rho_v = 0 \quad (3)$$

where ρ_v is the vapor concentration [kg m^{-3}], D_{va} is the binary diffusion coefficient between dry air and water vapor [$\text{m}^2 \text{s}^{-1}$] and $\mathbf{u}$ is the velocity vector [m s^{-1}].

Coupling of fruit and air domains

Appropriate conditions for heat and moisture exchange are required at the air-tissue interface to couple the two domains to one another. Conjugate modeling requires continuity of the heat and mass fluxes at each boundary interface element as well as continuity of the temperature and mass fraction at the interface (fluid-side: superscript fl; porous-material side: superscript pm). Continuity of the moisture and heat fluxes is specified as:

$$\mathbf{n} \cdot (-\mathbf{K}_m \nabla \psi)^{pm} = g_m = (-D_{va} \nabla \rho_v)^{fl} \cdot \mathbf{n} \quad (4)$$

$$\mathbf{n} \cdot (-h_l \mathbf{K}_m \nabla \psi - \lambda_{PM} \nabla T)^{pm} = g_T = (-\lambda_g \nabla T - h_v D_{va} \nabla \rho_v)^{fl} \cdot \mathbf{n} + q_{th} + q_s \quad (5)$$

where g_m [$\text{kg m}^{-2} \text{s}^{-1}$] and g_T [$\text{J m}^{-2} \text{s}^{-1}$] are the mass and heat fluxes at the interface, $\mathbf{n}$ is the unit vector normal to the interface, h_v and h_l are the enthalpies of water vapor and liquid water [J kg^{-1}], q_{th} and q_s are the heat fluxes due to thermal and solar radiation [$\text{J m}^{-2} \text{s}^{-1}$], respectively. Continuity of temperature and vapor concentration at the interface (T_w and $\rho_{v,w}$) is specified as:

$$T_w^{pm} = T_w^{fl} \quad (6)$$

$$\rho_{v,w}^{pm} = \rho_{v,w}^{fl} \quad (7)$$

Such boundary conditions are typical for conjugate modelling (Defraeye et al., 2012a; Erriguible et al., 2006) and are imposed across the entire interface of the fruit with the air domain. For mass transfer, the boundary condition states that moisture loss from the tissue equals the convective vapor removal from the surface via the boundary layer into the air. 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 via the boundary layer plus the heat removal due to the water vapor loss due to evaporation plus thermal radiation exchange of the tissue with the environment via the surface and solar radiation absorption at the fruit surface. Note that very few studies on fruit drying included radiation exchange in their model.

Apart from the conjugate heat and moisture exchange with the environment, also non-conjugate boundary conditions are evaluated at the air-tissue interface (Defraeye and Verboven, 2016), namely:

$$\mathbf{n} \cdot (-\mathbf{K}_m \nabla \psi) = g_m = h_{c,m} (p_{v,w} - p_{v,ref}) \quad (8)$$

$$\mathbf{n} \cdot (-h_l \mathbf{K}_m \nabla \psi - \lambda_{PM} \nabla T) = g_T = (h_{c,T} (T_w - T_{ref}) - h_v g_m) + q_{th} + q_s \quad (9)$$

where $h_{c,m}$ is the convective mass transfer coefficient (CMTC [s m^{-1}]), $h_{c,T}$ is the convective heat transfer coefficient (CHTC [$\text{W m}^{-2} \text{K}^{-1}$]), $p_{v,w}$ 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].

Constitutive equations

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

$$h_l = c_{p,l} (T - T_{\text{ref},0}) \quad (10)$$

$$h_v = c_{p,v} (T - T_{\text{ref},0}) + L_v \quad (11)$$

where L_v is the heat of vaporization [J kg^{-1}], also called latent heat, which is the energy needed for the phase change from liquid to vapor. $T_{\text{ref},0}$ is a reference temperature, taken equal to 273.15K (0°C). To determine the moisture

capacity $C_m = \frac{\partial w_m}{\partial \psi}$ (Eq. (1)), the sorption isotherm (w_m vs. water activity a_w) is required (in Table 1), as well as the

relation of water activity a_w to water potential ψ . The latter is given by:

$$\psi = \rho_l R T \ln(a_w) \quad (12)$$

The vapor pressures $p_{v,w}$ and $p_{v,ref}$, namely at the interface and of the approach airflow [Pa], are determined based on the water activity at the interface ($a_{w,w}$) and the relative humidity of the approach airflow (RH_{ref}), together with the corresponding temperatures (T_w and T_{ref} at the interface and of the approach airflow [K]), via the saturated vapor pressure ($p_{v,sat}$ [Pa]):

$$p_{v,w} = a_{w,w} p_{v,sat}(T_w) \quad (13)$$

$$p_{v,ref} = RH_{ref} p_{v,sat}(T_{ref}) \quad (14)$$

$$p_{v,sat}(T) = e^{\frac{65.8094}{T} - \frac{7066.27}{T^2} - 5.976 \ln T} \quad (15)$$

2.2 Analytical comparison

When evaluating drying processes by numerical modeling, it is always advised to verify the model results to see if the predictions are in the right range (Defraeye and Verboven, 2016). To this end, a comparison with the conditions during the constant drying rate period (CDRP) is useful, as detailed below. This CDRP is found during the first stage of the drying process. The CDRP is characterized by a high relative humidity (RH) at the surface ($\approx 100\%$), a constant drying rate and a constant material temperature. This temperature is equal to the wet bulb temperature (T_{wb}) if no radiative heat flow at the surface and (conductive) heat flows from the interior of the porous material are present. In this case, the convective heat supply to the interface is quasi entirely used for the evaporation of water. The drying rate during the constant drying rate period can be estimated analytically, namely by assuming a moist surface (RH $\approx 100\%$) which is at the wet bulb temperature. The wet bulb temperature can be determined from psychrometrics. From these conditions and those of the approach flow, the moisture flux during the CDRP can be calculated as follows:

$$g_m = h_{c,m} (p_{v,w,CDRP} - p_{v,ref}) \quad (16)$$

$$p_{v,w,CDRP} = a_{w,ini} p_{v,sat} (T_{wb}) \quad (17)$$

where $a_{w,ini}$ is the initial water activity of the fresh tissue, which was 0.9896 in the present study. This value is derived from the sorption isotherm, and corresponds to an initial moisture content of 780 kg m^{-3} , which was used in the numerical model (see below).

The CDRP drying rate is higher than for the subsequent decreasing drying rate period (DDRP), so it should be the maximal slope of the mass loss curve. The temperature during drying can be compared to the wet bulb temperature, where the latter should be the lowest temperature the material can attain, if the approach flow is at higher temperature, due to the high cooling caused by evaporation.

2.3 Computational model

Forced convective drying of a single fresh-cut apple slice, suspended in free-stream turbulent airflow, is modeled. In contrast to the square or rectangular geometries that have been applied so far in conjugate models of fruit drying, a half-circular slice (diameter $D = 75 \text{ mm}$) is considered. This particular shape is more challenging with respect to boundary-layer modeling than an angular (square) sample. The reason is that the boundary-layer separation point at the upper surface is not prescribed at a specific location (e.g. sharp corner), but is strongly dependent on the accuracy with which the boundary-layer flow is resolved.

A 2D model is constructed, thus assuming an infinite slice thickness. Although this 2D model differs from reality, this choice was made since: (1) the main aim was to obtain insight in physical processes during drying at the interface, and to verify the impact of modeling assumptions, which can both be illustrated on a 2D model; (2) the model complexity and computational cost are kept within limits as the present conjugate model is computationally very expensive, particularly since LRNM was applied to resolve the boundary layer. Drying of this 2D apple-slice configuration is used to evaluate different model assumptions and environmental conditions. The base case and variants that are simulated are detailed below.

Base case

The computational model and the imposed boundary conditions are specified in Figure 1. The upstream and downstream sections of the computational domain are taken sufficiently long to avoid an influence from inlet and outlet boundary conditions on the air flow in the vicinity of the fruit. Also the lateral boundaries are placed at a significant distance from the fruit.

At the domain inlet, a uniform bulk speed is imposed ($U_b = 1 \text{ m s}^{-1}$), which results in a Reynolds number of about 4800 for the base case, based on U_b and D . With the other variants that are considered (see below), a Reynolds number range between 480 and 48 000 is covered, which thus include the turbulent regime. A low turbulence

intensity (0.1%) is imposed at the inlet. The free-stream approach flow is kept at a constant temperature ($T_{ref} = 20^{\circ}\text{C}$) and relative humidity ($RH_{ref} = 60\%$). At the outlet of the computational domain, a zero static pressure is imposed. The lateral boundaries are modeled as slip-wall boundaries (symmetry), which assume that the normal velocity component and the normal gradients at the boundary are zero. The interface of the air with the fruit is modeled as a no-slip boundary for momentum transport, but exchange of heat and moisture between the two domains is enabled (see section 2.1).

Figure 1. Computational domain (not to scale) and boundary conditions.

The porous material is apple fruit (cv. *Braeburn*). The relevant material properties are specified in Table 1. The fruit is assumed to be initially (fresh-cut state) at a uniform moisture content $w_{m,ini}$ of 780 kg m^{-3} at a uniform temperature T_{ini} of 20°C . This moisture content leads to a dry-base moisture content X_{ini} of 6 ($= w_{m,ini}/w_s [\text{kg kg}_{dm}^{-1}]$).

An appropriate grid is built for air flow and the porous material domains, based on grid sensitivity analysis. The hybrid grid (quadrilateral and triangular finite elements) consists of 24 928 elements for the fruit domain and 103 700 elements for the air domain, leading to a total of 128 628 elements. A gradual refinement towards the air-porous material interface is used to enhance numerical accuracy and stability as the largest gradients occur there at the start of the drying process. As LRNM was applied to resolve the boundary layer, the boundary layer was explicitly discretized all the way down to the viscous sublayer. Note that radiation (long-wave and short-wave) at the interface is not modeled for the base case but is evaluated for specific variants.

Variants

Next to the base case, two types of variants were simulated (Table 2). A first type deals with different modeling assumptions, namely: (1) a simulation with a higher moisture permeability of the fruit tissue; (2) the use of constant CTCs (non-conjugate, Eq.(8-9)) instead of conjugate modeling for the drying simulations; (3) the use of isothermal conditions instead of non-isothermal ones; (4) including modeling of long-wave radiation exchange with the environment. A second type of variants (Table 2) involves changes in drying conditions: (1) different airflow conditions (speed), so CHTC and CMTC; (2) different approach flow humidities; (3) including solar radiation with high and very low airflow rates; (4) different approach flow temperatures.

For the non-conjugate simulations, the impact of airflow on the drying process is accounted for by means of convective transfer coefficients (CTCs). To this end, a constant value for the CHTC and CMTC is used over the entire

fruit surface, namely the surface-averaged CTCs from the conjugate simulations after 10 min of drying, in order to not have the peak CTC values at the start (see below).

Long-wave radiation exchange at the air-fruit surface (q_{th} , Eq.(5)) is modeled in a simplified way by assuming that the fruit is a relatively small object that is enclosed by a much larger surface (e.g. dryer), leading to a view factor of 1. This leads to the following equation (Datta, 2002):

$$q_{th} = \varepsilon_s \sigma_b (T_{w,d}^4 - T_w^4) \quad (18)$$

where ε_s the emissivity of the fruit surface (Table 1), σ_b is the Stefan-Boltzmann constant ($5.670 \times 10^{-8} [\text{W m}^{-2} \text{K}^{-4}]$) and $T_{w,d}$ is the surface temperature of the dryer surface [K]. $T_{w,d}$ is assumed here to be equal to the air temperature of the environment T_{ref} . The short-wave radiation adsorption is calculated as:

$$q_s = \alpha_s E_s \quad (19)$$

where α_s is the absorption coefficient of fruit (Table 1), and E_s is the solar irradiance, taken equal to 200 W m^{-2} . We assume only direct radiation onto the surface, with the same intensity all over the fruit surface. Although this is a simplification of reality, it will still allow us to estimate the impact of radiation on the drying process.

Table 2. Material properties and environmental conditions for different variants. If no value is specified (indicated by a dash), the same one is taken as for the base case.

Type 1: Modeling assumptions					
Variant name	Description				
Base case	Base case				
Km_8e-15	Higher tissue permeability (10 times higher: $K_m = 8 \times 10^{-16}$ s)				
Non-conj	Use of CTCs at the fruit interface (Eqs.(8-9)) instead of modeling the conjugate exchange with the airflow				
Isotherm	Isothermal conditions in the air and the fruit tissue by fixing the temperature ($T = 20^{\circ}\text{C}$)				
LWR	Long-wave radiation included at the air-tissue interface (Eq.(18))				
Type 2: Drying conditions					
Variant name	Speed U_b [m s ⁻¹]	Temperature T_{ref} [°C]	Humidity RH_{ref} [%]	Solar radiation E_s [W m ⁻²]	Long-wave radiation
Base case	1	20	60	0	No
RHref_10	-	-	10	-	-
RHref_30	-	-	30	-	-
RHref_75	-	-	75	-	-
RHref_90	-	-	90	-	-
Ub_0.1	0.1	-	-	-	-
Ub_10	10	-	-	-	-
Sol-LWR	-	-	-	200	Yes
Sol-LWR_LoSpeed	0.01	-	-	200	Yes
Tref_40	-	40	-	-	-
Tref_60	-	60	-	-	-

2.4 Numerical simulations

This model was implemented in COMSOL Multiphysics (version 5.0), which is a finite-element based modeling environment. To solve the transport in the porous material, the partial differential equations module (coefficient form) was used, in which the aforementioned conservation equations were implemented. Regarding the turbulent airflow modeling, the computational fluid dynamics (CFD) module of COMSOL Multiphysics was used. CFD has been extensively applied to model fluid flow for several food processing applications (Ambaw et al., 2013; Defraeye et al., 2012b; Norton et al., 2013). The accuracy of CFD simulations depends to a large extent on the turbulence-modeling and boundary-layer modeling approaches that are used. In this study, RANS was applied in combination with the SST

k- ω model. Low-Reynolds number modeling (LRNM) is used to resolve the transport in the boundary layer on the no-slip surfaces (e.g., fruit). The SST k- ω model in combination with LRNM was found to give the best model accuracy for convective flow and heat transfer around a single sphere (Defraeye et al., 2013b).

The model implementation was validated previously (results not reported) with the conjugate model results of (Defraeye et al., 2012a) and for turbulent flow with the results of (Defraeye et al., 2013b). The transport in the porous material is solved using a fully coupled solver to the dependent variables ψ and T . Airflow was solved using a segregated (staggered) solver. The tolerances for convergence and other solver settings were determined based on sensitivity analysis.

The simulations are performed in two steps. First, steady-state simulations of the airflow are performed to obtain the flow field and the initial temperature and vapor concentration conditions in the air. Secondly, the transient drying process is simulated. Since the flow field was assumed steady and stable over time as no buoyancy was included in the model, the flow field did not need to be recomputed anymore during the transient drying simulations. Thereby, the flow equations were switched off and only heat and vapor transport in the air were solved, by which the computational cost was significantly reduced. A drying process of 400 hours was simulated, starting from the specified initial conditions. All simulations applied adaptive time stepping, with a maximal time step of 600 s, as determined from a temporal sensitivity analysis.

3. RESULTS AND DISCUSSION

3.1 General drying characteristics

First, the fruit drying behavior is investigated for the base case. In Figure 2, the mass loss (dry base moisture content) and drying rate are shown versus time. In Figure 3, the surface-averaged temperature and relative humidity at the air-tissue interface are given, as well as their specific values at different locations on the fruit surface. The volume-averaged fruit temperature is also reported. Next to the base case, simulations with a higher moisture permeability (Km_8e-15) are evaluated, to indicate the impact of the moisture transport properties.

Figure 2. Comparison between simulations for base case and the case with 10 times higher moisture permeability (Km_8e-15): (a) dry base moisture content and (b) surface-average drying rate, as a function of time. The analytically-determined mass loss and drying rate at CDRP conditions are indicated with the dotted grey lines.

From Figure 2 and 3, it is clear that a CDRP is not present, even though the drying conditions (U_b , T_{ref} , RH_{ref}) are rather mild. The CDRP is characterized by an almost constant drying rate, so a linear moisture content change over time, and a constant (low) temperature and a high RH at the surface (Defraeye et al., 2012a). Most fruits are reported to have a very short CDRP or no CDRP at all, including apples (Ateeque et al., 2014; Ben Mabrouk et al., 2012; McMinn and Magee, 1999). The occurrence of a CDRP and its length are strongly dependent on the drying conditions and the moisture permeability of the tissue (Defraeye and Verboven, 2016). The analytical prediction of the CDRP drying rate (and corresponding mass loss), as well as the wet bulb temperature (section 2.2) prove to be simple but successful indicators (limits) to verify the predicted magnitudes of the drying kinetics.

Via simulations, the occurrence and duration of a constant drying rate period can be identified more precisely than in experiments. The reason is that quantities at the air-material interface, like moisture flux, temperature and relative humidity, which should remain quasi constant during the CDRP, can be determined accurately at any location on the fruit. In Figure 3, the fruit temperature clearly decreases below that of the ambient air, due to evaporation of water at the surface. Due to the slow evaporation process, only small temperature variations are found within the fruit,

rendering surface and volume-average temperatures almost equal. For the case with a higher permeability (K_{m_8e-15}), conditions closer to the CDRP are obtained, since the moisture transport from the tissue to the surface becomes less dominant over the transport from the surface to the environment via the boundary layer. Note that fruit should not necessarily be fully dried. In principle, it is sufficient to stop when the overall equilibrium water activity in the sample falls below the level at which no spoilage occurs anymore. For dried fruit, this water activity is about 0.6 (Bonazzi and Dumoulin, 2011).

In addition to the overall drying kinetics, the spatial variation in drying kinetics within the fruit is illustrated in Figure 3 and 4. In Figure 4, the distribution of the water activity in the fruit is shown at different points in time. The spatial variation in both heat and moisture exchange over the fruit surface is clear, showing differential drying within the fruit. The case with a higher permeability shows smaller (less steep) moisture gradients near the drying front inside the fruit. Especially in the wake zone, the drying is slower for the base case. This can be explained by looking at the moisture concentration in the airflow surrounding the fruit, as indicated in Figure 5, where the wake zone is clearly seen. Thereby the main advantage of the conjugate simulations is illustrated, namely that the heat and mass transport in both air and fruit can be evaluated simultaneously. This is indicated in Figure 6, where it is also clear that heat and mass transport have different time scales, as heat transfer is much faster. This is mainly caused by the different transport kinetics in the fruit tissue (heat conduction versus moisture diffusion).

Figure 3. Surface (-average) temperature (a-b) and corresponding relative humidity (or water activity) at the surface of the fruit (c), at different locations, indicated by dots in (d). The wet bulb temperature is indicated with the dotted grey lines. Note that the volume-average values are also indicated (dotted line).

Figure 4. Water activity a_w inside the fruit at different points in time for the base case, a case with a 10 times higher permeability and the non-conjugate case.

Figure 5. Relative humidity in the air at different points in time for the base case.

Figure 6. Relative humidity/water activity and temperature in the air and fruit tissue at a specific point in time for the base case.

As an alternative way of evaluating spatial variations in heat and mass exchange, convective transfer coefficients (CTCs) can be used, namely the convective mass transfer coefficient (CMTC, $h_{c,m}$ [$s\ m^{-1}$]) and the convective heat transfer coefficient (CHTC, $h_{c,T}$ [$W\ m^{-2}K^{-1}$]). CTCs can be considered as the inverse of the boundary layer resistance to heat or moisture transfer. These CTCs relate the convective heat and moisture flux normal to the wall ($g_{c,T}$ and $g_{c,m}$), i.e. the air-porous material interface, to the difference between the wall temperature (T_w) or vapor pressure at the wall ($p_{v,w}$) and a reference temperature (T_{ref}) or vapor pressure ($p_{v,ref}$), for example the approach flow conditions:

$$h_{c,t} = \frac{g_{c,T}}{T_w - T_{ref}} \quad (20)$$

$$h_{c,m} = \frac{g_{c,m}}{p_{v,w} - p_{v,ref}} \quad (21)$$

The fluxes are assumed positive away from the porous material.

In Figure 7, the CTCs at different locations on the fruit surface are shown as a function of time. In Figure 8, the CHTC and CMTC distribution over the upper and lower surface of the apple fruit are shown, at different points in time, namely for 2 hour intervals (first curve after 10 minutes). There is a distinct spatial variation and, to a lesser extent, a temporal variation of both CHTC and CMTC. The temporal variation is particularly pronounced at the start of the drying process. Negative CMTCs and CHTCs are found in the leading edge region on the lower edge of the fruit. Based on the definition of the CMTC (Eq.(21)), this implies that $g_{c,m}$ has to be negative since $p_{v,w}$ is always larger than $p_{v,ref}$ (dryer air, results not shown). As such, moisture is taken up by the fruit rather than being removed here. However, even for adsorption (rehydration), negative CMTCs are normally not found as in that case, the vapor pressure at the surface ($p_{v,w}$) is typically lower than that of the approach flow ($p_{v,ref}$). In the present study however, a counterintuitive

behavior is found as moisture adsorption occurs while the driving force for moisture transport (Δp_v) indicates the opposite ($p_{v,w} > p_{v,ref}$).

The explanation is found by looking at the local microclimate in that zone (Figure 5). Close to the lower edge, a recirculation zone exists which has a high humidity and temperature. As a result, the vapor pressure is quite high in the air layer in this zone, by which moisture migrates into the fruit locally. The driving force to calculate the transfer coefficients ($p_{v,w} - p_{v,ref}$), so based on $p_{v,ref}$, is thus not appropriate as it does not account for such locally humid microclimates. This local rehydration, so negative CMTCs, related to the local microclimate can only be captured by conjugate modeling.

Figure 7. CHTC and CMTC at different locations on the fruit surface as a function of time for the base case.

Figure 8. CHTC and CMTC distribution over the upper and lower surface of the apple fruit at different points in time (2 hour intervals, first curve after 10 minutes) for the base case. The surface of interest is indicated on the fruit slice drawing with a black bold line. The red arrows indicate the trend of the CTCs at increasing points in time.

3.2 MODELING

In this section, several modeling assumptions are evaluated to give insights in which physics to include in the hygrothermal model, and the impact of including them.

Conjugate modeling

Conjugate modeling is definitely not commonplace when simulating dehydration of porous materials, mainly due to the additional implementation effort and computational cost for explicitly solving turbulent airflow. Most often, constant CTCs are used to quantify the heat and mass exchange with the environment, so a non-conjugate approach. These CTCs are a simplified way to quantify the heat and mass transport in the boundary layer. Note that these CTCs are often taken from empirical correlations from literature, which makes that there is often no direct relation to the actual flow field of interest. In the present study however, already a significant improvement was made as the CTCs are estimated from the CFD calculation, namely the surface-averaged values.

The difference between the two strategies (conjugate versus non-conjugate) is identified in Figure 9. The conjugate approach is the most accurate option, as it avoids the use of a-priori estimated CTCs. However, with respect to the overall drying behavior, for example total mass loss, both provide similar results. The main reason is that the impact of CTCs is particularly relevant during the CDRP and during the transition to the DDRP, i.e. when the surface is (partially) wet, since then the air flow mainly determines the drying rate. During the DDRP, the transport inside the fruit tissue dominates the drying kinetics. As such, the need for detailed modeling of the convective boundary conditions, e.g. by means of conjugate modeling, is strongly dependent on the moisture transport inside the material. The apple fruit has a low moisture permeability, so no CDRP for the present drying conditions. Thereby, the spatial and temporal variation in CTCs have a very small impact on the drying predictions. Recent research showed that the sensitivity to the CHTC is larger than to the CMTC (Defraeye and Verboven, 2016), so accurate estimates of CHTCs are particularly critical. For CMTCs, empirical values from literature could be sufficiently accurate.

The conjugate approach however has the additional advantage that specific details, such as local rehydration (negative CMTCs, Figure 8, section 3.1), can be captured, since the local microclimate surrounding the fruit is modeled. Also local variations in internal moisture distribution between leading and trailing edge of the fruit can be observed, compared to the non-conjugate approach (Figure 4). Conjugate modeling provides insight in the flow, temperature and humidity field around the fruit (Figure 5-6). Thereby the relation between inhomogeneities in the airflow and those in the tissue can be identified in a single simulation. Such insight is also of interest when considering drying of several fruits which are located downstream of one another in a dryer, as the airflow will become more humid further downstream.

However, the need for a conjugate approach needs to be assessed case by case, by estimating the transfer in the boundary layer versus the transfer in the tissue. For most fruits, the transport inside the material will be the limiting factor over convective mass transfer via the boundary layer. The drying kinetics however still remain strongly sensitive to the CHTC (Defraeye and Verboven, 2016), as the convective heat supply to the tissue via the boundary layer is essential to evaporate water.

Isothermal modeling

For slow dehydration processes, sometimes isothermal conditions are assumed (e.g. (Aregawi et al., 2013b)). This reduces model complexity as only the moisture transport equation needs to be implemented. We verify the impact of this assumption in Figure 9. Even for the mild drying conditions that were used here, where approach flow temperature equals the initial fruit temperature and the relative humidity is quite high, significant differences with the base case are found. The drying rate is higher in the isothermal case since the vapor pressure at the surface, so the driving force for convective mass transfer, is larger. It is clear that the isothermal assumption should preferably not be used, even for near-isothermal conditions, such as low-temperature drying.

Figure 9. Dry base moisture content (a), surface-average drying rate (b), surface (-average) temperature (c) and corresponding relative humidity (or water activity) at the surface of the fruit (d) under different modeling assumptions as a function of time. The analytically-determined mass loss, drying rate and wet bulb temperature at CDRP conditions are indicated with the dotted grey lines.

Long-wave radiation

Thermal radiation exchange with the environment is often left aside in convective drying models, particularly in conjugate modeling studies (Defraeye, 2014). The main argument is that convective heat transfer is much larger than radiative transfer and/or that the temperature differences between fruit surface and environment are limited. In

Figure 9, the impact of this assumption is quantified. Even for the small temperature difference of the fruit with the environment (assumed at 20°C), the impact of thermal radiation can be observed. Therefore, it is advised to include thermal radiation in future studies, also in conjugate modeling. Note however that the implementation of long-wave radiation was simplified and subject to certain assumptions, and becomes more elaborate for complex configurations. Particularly for large temperature differences between the cold fruit surfaces and the warm dryer chamber walls, thermal radiation will be important.

3.3 DRYING CONDITIONS

Air speed and approach flow temperature

The impact of different air speeds and approach flow temperatures is analyzed in Figure 10. Given the large airspeed range that is considered (factor 100), its impact on the drying process can be considered relatively small. Previous studies (Defraeye and Verboven, 2016) showed this impact is strongly related to the magnitude of the moisture permeability of the tissue. Nevertheless, drying at high speeds (e.g. 10 m s^{-1}) clearly increases the drying rate. It has to be kept in mind however that increasing the speed to enhance the drying rate can have a serious impact on the energy consumption of the drying facility, as the fan power typically scales with the cube of the air speed. It can be more effective to just work with dryer air (see below). Furthermore, drying at a higher temperature but at the same speed and humidity has an impact on the drying rate, but not that large. The impact of the drying temperature is expected to become larger for three-dimensional samples, as then the surface area through which evaporation can take place is larger. Note also that the relative humidity of the approach flow air was kept the same at each temperature in this study, whereas in experiments, higher temperatures are often accompanied by a lower humidity of the drying air. For heat sensitive materials, such as many foods, temperatures should preferably be kept low.

Figure 10. Dry base moisture content for different air speeds and approach flow temperatures as a function of time.

Approach flow humidity

Next to changing the boundary layer resistance, so CMTC, the driving force for moisture transport can also be altered. In Figure 11, the impact of different approach flow humidities is shown. Changing the humidity has a significant effect on the drying rate, compared to the air speed and the approach flow temperature. In addition, it is clear from Figure 11 that the CTCs vary in space and time in a different way for different approach flow humidity levels.

Figure 11. Dry base moisture content (a), average temperature at the surface of the fruit (b), surface-average CHTC (c) and CMTC (d) on the fruit surface under different humidity conditions of the drying air, as a function of time. The CHTC and CMTC are scaled with the value near the start of the drying process (after 10 min).

Solar radiation

The impact of solar radiation, with airflow (Sol-LWR) and with very low airflow rates (Sol-LWR_LoSpeed), is shown in Figure 12, as compared to the base case. Note that long-wave radiation exchange with the environment is included in these simulations. Also note that for all cases, the temperature at the surface and inside the fruit were very similar. Solar drying without convection provides a drying rate that is higher than the base case, with very high fruit temperatures. Combined convective/solar drying (Sol-LWR) leads to the fastest drying, although the surface temperatures are not that high as without convection. The airflow clearly provides cooling of the surface when solar radiation is present. The higher temperatures due to solar radiation can be detrimental for fruit quality as heat-sensitive compounds can degrade. As such, for direct solar drying, convection can have a positive effect on the fruit quality and also enhances moisture removal from the surface.

Figure 12. Dry base moisture content (a), surface temperature at the surface of the fruit (b) under different solar radiation conditions, as a function of time.

5. CONCLUSIONS

Validated conjugate modeling of turbulent convective drying of a half-circular fruit slice was used to investigate: (1) the impact of several model assumptions, including the need for applying a conjugate approach over a non-conjugate one, (2) different drying conditions including solar radiation. Conjugate modeling implies that the heat and mass transport in both air and fruit are solved simultaneously.

Although a conjugate model is inherently more accurate, the gain in accuracy with the non-conjugate approach, which just uses convective heat and mass transfer coefficients (CTCs) to quantify the convective exchange, was limited in terms of overall fruit drying kinetics, such as total mass loss. Note however that in this study, the CTCs for the non-conjugate approach were obtained from the conjugate simulations, whereas other studies use less accurate CTCs as they are taken from literature, rather than being explicitly calculated. Nevertheless, conjugate modeling allowed to identify spatial and temporal variability in CTCs, which locally affected drying rates and the internal moisture distribution. Thereby, we identified the occurrence of negative CTCs, which led to rehydration at specific locations on the fruit surface, due to the surrounding high-humidity microclimate. The ability to identify the direct relation between inhomogeneities in the airflow to those in the tissue is a unique trait of the conjugate approach. Furthermore, it was shown that isothermal modeling should not be used, even for near-isothermal conditions such as low-temperature drying, and that thermal radiation exchange with the environment should preferably be accounted for.

Regarding the drying conditions, the impact of the air speed and approach flow temperature was found to be smaller than altering the approach flow humidity. When direct solar radiation was present, airflow provided significant cooling of the fruit, which is beneficial for preserving heat-sensitive nutritional compounds in the fruit, and it also enhanced the drying rate.

Some model improvements could be made in the future. A 3D model of the fruit slice could be targeted, which however will entail a very large computational cost if conjugate modeling is applied. Implementing moisture and thermal transport properties (e.g. permeability) that are dependent on the temperature, moisture content and shrinkage would further enhance the accuracy and application range of the simulations. However, the required material characterization is extensive and seldom undertaken prior to a modeling study. Mechanical deformation due to tissue shrinkage could be included as well, but also fruit quality prediction models could be implemented. The latter estimate degradation of fruit nutrients (e.g. vitamins), based on reaction kinetics and the time-temperature history of the tissue.

ACKNOWLEDGEMENTS

We acknowledge the support of the World Food System Center (WFSC) of ETH Zürich (www.worldfoodsystem.ethz.ch). We also acknowledge the support of the Swiss National Science Foundation SNSF (project 200021_160047).

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