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# 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.



## 1. Introduction

Convective drying is an important unit operation to process food material and to preserve highly-perishable foods, such as fresh produce [15,35]. 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 [7,8,23,42] or solar pervaporation [38] 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 [28] and solar-assisted drying [36], where the latter is subject to fluctuations in incident radiation

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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 [3,18,21,25,39].

Although experiments on fruit drying [40,41,43] 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 [11,15]. 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. [13,26,29,31,30,32]) 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 [1,22,16]. 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 ([17] based on [27]), but adjustments are made to the porous medium model to account for the case of apple fruit drying (see [20]). 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 [17,20].

#### 2.1.1. Porous medium model

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

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

$$h_l C_m \frac{\partial \psi}{\partial t} + C_{m,T} \frac{\partial T}{\partial t} + \nabla \cdot (-h_l K_m \nabla \psi) + \nabla \cdot (-\lambda_{PM} \nabla T) = 0 \tag{2}$$

where $C_m$ is the moisture capacity ($C_m = \frac{\partial w_m}{\partial \psi}$), $C_{m,T}$ is the thermal capacity term (=$c_{p,s} w_s + c_{p,l} w_m$), where $w_s$ and $w_m$ are the dry matter content (solid) and moisture content of the tissue [kg m$^{-3}$], respectively, and $c_{p,s}$ and $c_{p,l}$ are the specific heat capacities of dry matter and liquid water [J kg$^{-1}$ K$^{-1}$], respectively. $K_m$ is the moisture permeability of the tissue [s], $h_l$ is the enthalpy of liquid water [J kg$^{-1}$], $\lambda_{PM}$ is the thermal conductivity of the tissue (moist porous medium, so including water) [W m$^{-1}$ K$^{-1}$]. These material properties are given in Table 1. $K_m$ and the sorption isotherm were determined earlier [4]. Note that to close the set of equations, the moisture content ($w_m$) is still required, which can be inferred from the water potential ($\psi$) as follows. The moisture content can be directly quantified from the water activity ($a_w$) via the sorption isotherm ($w_m(a_w)$ relationship), which is specified in Table 1. The water activity, in turn, is directly related to the water potential:

$$\psi = \rho_l R_v T \ln(a_w) \tag{3}$$

where all constants are defined in Table 1. Based on this relation, the moisture capacity $C_m$ can be inferred from the sorption isotherm ($w_m(a_w)$).

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 modeling of fruit drying [15]. 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

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

| Material properties | Symbol | Value |
|---|---|---|
| Moisture permeability fruit tissue | $K_m$ | $8 \times 10^{-16}$ [s] |
| Thermal conductivity fruit tissue | $\lambda_{PM}$ | 0.418 [W m$^{-1}$ K$^{-1}$] |
| Specific heat capacity dry matter | $c_{p,s}$ | 1634 [J kg$^{-1}$ K$^{-1}$] |
| Specific heat capacity liquid water | $c_{p,l}$ | 4182 [J kg$^{-1}$ K$^{-1}$] |
| Specific heat capacity water vapor | $c_{p,v}$ | 1880 [J kg$^{-1}$ 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 | $\rho_l$ | 1000 [kg m$^{-3}$] |
| Latent heat | $L_v$ | $2.5 \times 10^6$ [J kg$^{-1}$] |
| Specific gas constant for water vapor | $R_v$ | 461.52 [J kg$^{-1}$ K$^{-1}$] |
| Binary diffusion coefficient of water vapor in air | $D_{va}$ | $2.31 \times 10^{-5} \left(\frac{T}{273.16}\right)^{1.81}$ [m$^2$ s$^{-1}$] |
| Emissivity of the fruit surface | $\varepsilon_s$ | 0.95 |
| Absorption coefficient of short-wave radiation | $\alpha_s$ | 0.5 |