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Continuum-scale modeling of superheated steam drying of cellular plant porous media

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ABSTRACT

In this work, a continuous model is developed to describe the dynamics of heat and mass transfer in cellular plant porous media during the superheated steam drying process at atmospheric pressure. This model accounts for the advective liquid and vapor flows in the intercellular void space as well as for the diffusive liquid flow across the solid cell membranes of the porous medium. The numerical results are verified against drying experiments for potato samples, which were carried out by a magnetic suspension balance at three different superheated steam temperatures (160 °C, 180 °C, 200 °C). A comparison between the simulation results and the measured data shows that the drying characteristics of a plant porous medium can fairly be predicted by using the continuous model developed herein. The influence of the cell membrane water conductivity on the spatio-temporal distribution of the moisture content and of the temperature within the porous medium is studied by numerical simulations. It is observed that the water diffusion across the cell membranes controls the dynamics of the heat and mass transfer in the porous medium, and thus the drying kinetics.

1. Introduction

Drying plays a crucial role in the processing of plant porous materials with delicate cellular structures (i.e. fruits and vegetables). Because the quality preservation of these biological materials in drying is of essential importance, it should not be handled in an empirical way of trial and error. As an alternative, rigorous mathematical models based on the fundamental physical laws governing porous material drying have been developed to explore and assess the influence of both process conditions and material properties on the final quality of dried products.

Traditionally, hot air with sufficient moisture uptake capacity is employed as the drying agent in a convective drying system, which is referred to as hot air drying (HAD). In recent years, with emerging technological advancement in design, construction and computer control, coupled with the high energy price and strict environmental regulations, superheated steam drying (SSD) has been commercialized and applied in agricultural and food industries for drying cellular plant products such as wood chips [1], rice [2], potato [3,4], banana [5]. This drying technique has advantages over HAD essentially in terms of energy-saving and product quality [6–8]: The latent heat of the exhaust steam can be recycled by using condensation. The vapor generated inside the porous product during the SSD process has high pressure which makes the solid structure more robust against capillary forces, resulting in a porous structure with higher porosity compared to HAD. Consequently, the superheated steam dried products often yield lower bulk density and higher rehydration capacity. The products dehydrated by means of SSD may be brighter since both oxidation and combustion reactions that require oxygen from the gas phase are suppressed [7,9]. Although SSD has been applied successfully in various industries [6], there is still a very strong need for both tailored mathematical models and measurement techniques so as to study the mechanism of superheated steam drying of plant porous materials and their characteristics.

The microscopic anatomy has revealed that the skeleton of fresh plant tissues generally has a reticulated character with individual cells. These cells are enclosed with semi-permeable walls. As stated in the literature, e.g. [10,11], in a fresh plant such as potato, eggplant, or cucumber, more than 90% of the total moisture exists inside the cell matrix, the so-called intracellular moisture; only 5–10% of the total moisture is accumulated in the intercellular void space, named the extracellular moisture. A common understanding is that during the drying process the intracellular moisture is transported outwards through the cell walls into the

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Nomenclature

A_v	specific internal area per unit volume, $m^2\ m^{-3}$
c_p	specific heat capacity at constant pressure, $J\ kg^{-1}\ K^{-1}$
d_s	characteristic diameter, m
h	specific enthalpy, $J\ kg^{-1}$
Δ_{hevp}	evaporation latent heat, $J\ kg^{-1}$
j	water diffusion flux, $kg\ s^{-1}\ m^{-2}$
K	absolute permeability, m^2
K_r	relative permeability, –
k_p	water conductivity of the cell membrane, $m^3\ N^{-1}\ s^{-1}$
L	thickness, m
$\dot{m}_v$	volumetric evaporation flux, $kg\ s^{-1}\ m^{-3}$
$\dot{m}_{drying}$	drying flux, $kg\ s^{-1}\ m^{-2}$
M	mass, kg
$\tilde{M}_v$	molar mass of water, $kg\ mol^{-1}$
$\dot{M}_{steam}$	mass flow rate of steam, $kg\ s^{-1}$
p	pressure, Pa
R	universal gas constant, $J\ K^{-1}\ mol^{-1}$
T	temperature, °C
t	time, s
v	velocity, $m\ s^{-1}$
X	moisture content, kg water kg dry $solid^{-1}$

Greek symbols

α	heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
δ	thermal emissivity, –
ε	volume fraction, –
λ	thermal conductivity, $W\ m^{-1}\ K^{-1}$
μ	dynamic viscosity, Pa s
υ	kinematic viscosity, $m^2\ s^{-1}$
ρ	mass density, $kg\ m^{-3}$
σ	surface tension, $N\ m^{-1}$
σ_{rad}	Stefan-Boltzmann constant, $W\ m^{-2}\ K^{-4}$
ϕ	water potential, Pa
φ	sorption isotherm, –
ψ	porosity, –

Subscripts/superscripts

c	capillary
$conv$	convection
cr	critical
eff	effective
ex	extracellular
in	intracellular
l	liquid
n	normalized
v	vapor
rad	radiation
ref	reference
s	solid
sat	saturation
sh	shrinkage
$surf$	surface
v	vapor
w	water
0	initial value

intercellular openings which are large enough to transport the fluid towards the external surface of the tissue structure [12]. Based on this understanding several mathematical models accounting for various physical effects have already been formulated to predict the drying characteristics of biological materials.

A coarse way to model SSD is to opt for the empirical models such as Page model, single term and two term exponential equations [13]. Another class of models were developed based on Fick's second law of diffusion and the concept of an effective moisture diffusion coefficient [14–20], which is a phenomenological point of view. In these models, the moisture flow is not subdivided into liquid and gas mixture flow; it is, instead, treated as a one-phase flow and the effective moisture diffusion coefficient is fitted from the evolution of moisture content over time. A summary of the diffusion models can be found in literature, for example, see [21]. Despite the ability of the cited kind of models to predict the evolution of mean moisture content over time, a detailed understanding of fluid flow and evaporation process in a cellular plant porous medium cannot be gained due to the aforementioned simplification where the transport resistance of the liquid-vapor flow created in both intercellular void space and cell membrane are lumped together in the effective diffusivity, a fitting parameter. Furthermore, for intensive drying processes such as superheated steam drying where the contribution of vapor convection to overall moisture transport is significant, the diffusion models may not be predictive enough [22]. Several continuous models that take into account both liquid and vapor transport based on the volume averaging technique were also developed to simulate the plant drying process [1,23–25]. In these models, the cellular plant tissue is considered as a rigid porous medium. The intracellular moisture is considered to be bound moisture and the membrane resistance for water transport is lumped in the sorption isotherm.

In the context of hot air convective drying (HAD), the most rigorous continuous models developed for the isothermal process of cellular plant porous media take into account both the diffusion of intracellular moisture across the cell membrane and the two phase fluid flow in the intercellular void space [26–28]. However, there exists no equivalent model in the literature that describes the superheated steam drying process of cellular plant porous media. Therefore, our major motivation in this work is to couple the diffusive water flow across the cell membranes with thermal effect in order to provide a better understanding of non-isothermal fluid flow involved in a cellular plant porous medium. The model-based studies performed in this work can also pave the way to optimize both the process energy consumption and the product quality.

In this work, a continuous model based on first principles is developed that accounts for the conjugate heat and mass transfer in a cellular plant porous medium during superheated steam drying at atmospheric pressure. In this model, the advective fluid flow within the intercellular void space is coupled with the diffusive flow across the cell membrane under the thermal effects. The model description including the constitutive relations required to close the set of conservation equations is presented. Numerical simulations are performed for a potato sample serving as the drying product. The simulation results are qualitatively validated by comparing against experimental data measured by a magnetic suspension balance. Next, a model-based sensitivity analysis is performed to delineate the influence of cell membrane water conductivity on the drying behavior of the potato sample. Finally, conclusions of this work are drawn.

2. Model description

Cellular plant porous material is comprised of several types of cells such as parenchyma, collenchyma, and solute-conducting cells [29]. In this work, we consider the drying process in a tissue structured by parenchyma cells which are a primary component