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Research Paper

Numerical investigation of plant tissue porosity and its influence on cellular level shrinkage during drying

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Dried plant food products are increasing in demand in the consumer market, leading to continuing research to develop better products and processing techniques. Plant materials are porous structures, which undergo large deformations during drying. For any given food material, porosity and other cellular parameters have a direct influence on the level of shrinkage and deformation characteristics during drying, which involve complex mechanisms. In order to better understand such mechanisms and their interrelationships, numerical modelling can be used as a tool. In contrast to conventional grid-based modelling techniques, it is considered that meshfree methods may have a higher potential for modelling large deformations of multiphase problem domains. This work uses a meshfree based microscale plant tissue drying model, which was recently developed by the authors. Here, the effects of porosity have been newly accounted for in the model with the objective of studying porosity development during drying and its influence on shrinkage at the cellular level. For simplicity, only open pores are modelled and in order to investigate the influence of different cellular parameters, both apple and grape tissues were used in the study. The simulation results indicated that the porosity negatively influences shrinkage during drying and the porosity decreases as the moisture content reduces (when open pores are considered). Also, there is a clear difference in the deformations of cells, tissues and pores, which is mainly influenced by the cell wall contraction effects during drying.

1. Introduction

Food drying is a global industry providing a significant contribution to the food supply chain and economies. Among the different varieties of dried food products, plant-based products have a high popularity, mainly due to their natural source and balanced nutritional content. Since plant food materials contain a higher moisture content (usually about 90%), they are highly susceptible to microbial spoilage

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Nomenclature

A	cell top surface area (m^2)
A_0	cell top surface area at fresh condition (m^2)
A/A_0	normalised cell area
A_c	total surface area of the cylindrical cell (m^2)
C	cell compactness
C_0	cell compactness at fresh condition
C/C_0	normalised cell compactness
D	cell Feret diameter (m)
D_{major}	cell major axis length (m)
D_{minor}	cell minor axis length (m)
D_0	cell Feret diameter at fresh condition (m)
D/D_0	normalised cell Feret diameter
E	Young's modulus of the cell wall material (MPa)
EL	cell elongation
EL_0	cell elongation at fresh condition
EL/EL_0	normalised cell elongation
$\mathbf{F}^e$	cell wall stiff forces (N)
$\mathbf{F}^d$	cell wall damping forces (N)
$\mathbf{F}^{rf}$	wall-fluid repulsion forces (N)
$\mathbf{F}^{rw}$	wall–wall repulsion forces (N)
$\mathbf{F}^a$	wall-fluid attraction forces (N)
$\mathbf{F}^b$	forces due to the bending stiffness of the wall (N)
$\mathbf{F}^p$	cell fluid pressure forces (N)
$\mathbf{F}^v$	cell fluid viscous forces (N)
G	shear modulus of the cell wall material (MPa)
K	cell fluid compression modulus (MPa)
L	width of a given discrete wall element (m)
L'	width of a given discrete wall element at fully turgid state (m)
L_0	initial width of a given discrete wall element (m)
L_p	cell wall permeability ($m^2\ N^{-1}\ s$)
P	cell perimeter (m)
P_0	cell perimeter at fresh condition (m)
P/P_0	normalised cell perimeter
P_a	pressure of any fluid particle a (Pa)
P_T	initial cell turgor pressure (Pa)
R	cell roundness
R_0	cell roundness at fresh condition
R/R_0	normalised cell roundness
S	ratio between fluid inter-particle distance and smoothing length (r_{ab}/h)
T	cell wall thickness (m)
T_0	initial cell wall thickness (m)
TP	positive cell turgor pressure effects
W	smoothing kernel
WD	cell wall contraction effects
WC	cell wall drying effects
X	x – coordinate axis
X	dry basis moisture content ($kg_{water}/kg_{dry\ solid}$)
X_0	dry basis moisture content at fresh condition
X/X_0	dry basis normalised moisture content
Y	y – coordinate axis
Z	cell height (m)
Z	z – coordinate axis
Z_0	initial cell height (m)
Z_t	cell height at the previous time step (m)
$Z_{t+\Delta t}$	cell height at the current time step (m)
f_0^{rf}	strength of the LJ repulsion forces between fluid and wall particles ($N\ m^{-1}$)
f_0^{rw}	strength of the LJ repulsion forces between non-bonded wall particles ($N\ m^{-1}$)
f_0^a	strength of the LJ attraction forces between fluid and wall particles ($N\ m^{-1}$)
h	smoothing length (m)
h_0	initial smoothing length (m)
k_b	bending stiffness of cell wall material ($N\ m\ rad^{-1}$)
k_{wc}	force coefficient of cell wall contractions ($N\ m^{-1}$)
m_a	mass of any particle a (kg)
n_f	cell fluid particle number
n_w	cell wall particle number
r	cell radius (m)
r_{ab}	distance between any given particle a and b (m)
t	time (s)
$\boldsymbol{v}_{ab}$	velocity of any given particle a relative to any other particle b ($m\ s^{-1}$)
$\boldsymbol{x}_{ab}$	position vector of any given particle a relative to any other particle b (m)
Δt	time step (s)
x_0	initial fluid grid spacing (m)
$\Delta\theta$	change of external angle θ of any given wall element (rad)
$\Delta\boldsymbol{x}_{ab}$	change of gap difference of any two particles a and b compared to their initial gap (m)
Π	osmotic potential of the cell (Pa)
α	factor governing the relationship between z-directional extension ratio and λ_θ of any wall element
β	parameter that relates 2-D deformations to 3-D deformations of any wall element
γ	cell wall damping constant ($N\ m^{-1}\ s$)
ε_0	initial minimum allowed gap between outermost fluid particles and cell wall particles (m)
θ	external angle between any adjacent cell wall elements (rad)
λ_θ	extension ratio of any given cell wall element
μ_a	dynamic viscosity of any fluid particle a (Pa s)
ρ_a	density of any given fluid particle a ($kg\ m^{-3}$)
ρ_0	initial density of the cell fluid ($kg\ m^{-3}$)
ρ_a^*	2-D density of any given particle a ($\rho_a^* = Z\rho_a$) ($kg\ m^{-2}$)

(Jangam, 2011). About 20% of the world's perishable crops are subjected to drying, mainly for preservation purposes (Grabowski, Marcotte, & Ramaswamy, 2003), with a variety of drying techniques being used (Martin, Osvaldo, Ganesan, Rakesh, & Weitnauer, 2006). Some of the critical phenomena that food structures can experience during drying include; shrinkage (Karunasena, Hesami, et al., 2014; Han, Yin, Li, Yang, & Ma, 2010; Hills & Remigereau, 1997; Lee, Salunkhe, & Nury, 1967; Lewicki & Drzewucka, 1998; Mayor, Silva, & Sereno, 2005; Ramos, Silva, Sereno, & Aguilera, 2004;