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Modeling of internal moisture transport during durum wheat pasta drying

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ABSTRACT

A mechanistic model considering water evaporation and distinguishing liquid water and water vapor transport during pasta drying was developed and validated with published experimental moisture profiles. Model predictions of the internal moisture profiles were more accurate and able to capture the evolution with time of the moisture profiles for drying at low and high air temperatures. Model simulations indicated that approximately 88% of the water is transported in the liquid state, the convective flow of liquid water is negligible and the diffusion and convection of water vapor are important. A sensitivity analysis showed that the diffusivities and the mass transfer coefficients were the parameters affecting the most significantly the model drying time and internal moisture profile estimates.

1. Introduction

Over the years, numerous studies have demonstrated the importance of the air temperature and relative humidity conditions for the drying of pasta and the production of pasta with desired moisture and quality attributes (Manthey and Schorno, 2002; Zweifel et al., 2003; Mercier et al., 2011). Yet, the temperature and relative humidity profiles of the drying chamber for industrial pasta operations are determined mainly by trial-and-error. This method is expensive and time consuming because of the numerous potential operating conditions of pasta processing.

Models represent an attractive approach to reduce the time for the identification of appropriate drying conditions and achieve the required water removal for the production of dried pasta. To date, the modeling of the water transport during pasta drying is based on a Fick-type law relationship with a lumped parameter, the effective diffusion coefficient (D_{eff}), to represent the water mass transfer (Andrieu and Stamatopoulos, 1986). Published experimental results (Andrieu and Stamatopoulos, 1986; Migliori et al., 2005; DeTemmerman et al., 2007 and Mercier et al., 2013a) indicate that models based on the lumped effective diffusion coefficient provide accurate estimation for the evolution of the total water content of pasta during drying but are unable to capture the internal moisture profiles (Litchfield and Okos, 1992; Hills et al., 1997; Xing et al., 2007). The estimation of internal water profiles during pasta drying is critical for tailoring the pasta properties, the minimization of crack formation and propagation and achieving uniform glass transition conditions (Ponsart et al., 2003; Mercier et al., in press). Improved representation of the internal water profiles and understanding of the water mass transfer mechanisms can be obtained with the development of mechanistic models from mass, heat and momentum balances for each component and phase of the system. When considering pasta as a porous and hygroscopic material with water evaporation taking place during drying, the water mass transfer will consist of liquid water and water vapor flow. Liquid water flow will be mainly composed of capillary diffusion, resulting from the relative attraction of the liquid water molecules for each other and for those of the solid, and convection. Water vapor flow will be mainly composed of molecular diffusion and convection (Datta, 2007). The distinction of the flow of liquid water and water vapor may improve the internal moisture profile estimates as suggested by Litchfield and Okos (1992) while the distinction of the diffusive water flow and the convective water flow would provide a detailed representation of the mass transfer mechanisms taking place during drying. Similar water transport mechanistic models have been developed for bread baking revealing the

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Nomenclature

a_w	water activity, –
c	concentration, kg m^{-3}
C_P	heat capacity, J kg^{-1} K^{-1}
D	diffusion coefficient, m^2 s^{-1}
E_a	activation energy, J mol^{-1}
f	output parameter for the sensitivity analysis (Eq. (31))
h	surface mass (m s^{-1}) or heat (W m^{-2} K^{-1}) transfer coefficient
H	specific enthalpy, J kg^{-1}
k	permeability, m^2
k_h	thermal conductivity, W m^{-1} K^{-1}
K_{ev}	evaporation rate constant, s^{-1}
I	evaporation rate, kg m^{-3} s^{-1}
l	coordinate for thickness, m
L	pasta half-thickness, m
MW	molecular weight, Dalton
n	mass flux, kg m^{-2} s^{-1}
P	pressure, Pa
R_g	ideal gas constant, J mol^{-1} K^{-1}
RH	relative humidity, %
Sr	relative sensitivity, –
t	drying time, s
T	temperature, K
V	volume, m^3
x	mass fraction in the gas phase, –
X	pasta water content on dry basis, kg H_2O (kg dry solid)$^{-1}$
z	mass fraction in the pasta, –

Greek symbol

ϵ	porosity, water vapor m^3 (gas phase m^3)$^{-1}$
λ	latent heat of vaporization, J kg^{-1}
η	volumetric fraction of water lost replaced by air, –
ξ	local shrinkage, –
ρ	density, kg m^{-3}
τ	pore tortuosity, –
μ	viscosity, kg m^{-1} s^{-1}

Subscripts

0	initial condition
a	air
app	apparent
eff	effective
e	energy
eV	evaporation
E	equilibrium
f	at film conditions
g	gaseous phase
h	heat
liq	liquid phase
m	mass
M	moisture (i.e. liquid water + water vapor)
s	dry solid
v	water vapor
w	liquid water

importance of moisture convection and evaporation in the baking process (Zhang and Datta, 2006; Ousegui et al., 2010).

The aim of this work was to investigate water evaporation and distinguish the internal liquid water and water vapor transport by diffusion, capillarity and convection during pasta drying. A mechanistic model was developed, validated with published experimental internal moisture profiles, and compared to estimates obtained from existing models. The potential of the model to serve as tool for the analysis of the mass and heat transfer mechanisms taking place during pasta drying will also be discussed.

2. Methodology

2.1. Mathematical modeling

2.1.1. Hypothesis

The model was developed for a slab of pasta having a high surface/thickness ratio. The following assumptions were made: (1) mass and heat transfer only occurs in the direction of thickness; (2) the surface of the pasta is exposed symmetrically to the air in the drying chamber; (3) the gas phase in the pasta consists of air and water vapor and behaves as an ideal gas; (4) the gas, liquid and solid phases of the pasta have the same local temperature; (5) the water vapor diffuses only in the gas phase; (6) the surface of the pasta is at atmospheric pressure; (7) water in the vapor phase is exchanged between the pasta and the drying chamber and (8) the temperature and relative humidity of the air in the drying chamber are constant.

2.1.2. Mass transfer

Mass balances were developed for the liquid water, the water vapor and the total gas phase (water vapor + air) as follows:

$$\frac{\partial C_w}{\partial t} = \frac{\partial n_w}{\partial l} - I \quad (1)$$

$$\frac{\partial C_v}{\partial t} = \frac{\partial n_v}{\partial l} + I \quad (2)$$

$$\frac{\partial C_g}{\partial t} = \frac{\partial n_g}{\partial l} + I \quad (3)$$

where C_w, C_v and C_g are the mass concentration of liquid water, water vapor and total gas phase, l the coordinate for the pasta thickness and I the water evaporation rate. The mass flux of the individual components (n_w, n_v and n_g) includes liquid water capillary diffusion, water vapor molecular diffusion and convective moisture transport, the latter being described with Darcy's law (Bird et al., 1960):

$$n_w = D_w \frac{\partial c_w}{\partial l} + \rho_w \frac{k_w}{\mu_w} \frac{\partial P}{\partial l} \quad (4)$$

$$n_v = C_g \, D_{v,eff} \frac{\partial x_v}{\partial l} + \rho_v \frac{k_g}{\mu_g} \frac{\partial P}{\partial l} \quad (5)$$

$$n_g = \rho_g \frac{k_g}{\mu_g} \frac{\partial P}{\partial l} \quad (6)$$

where D_w and $D_{v,eff}$ are the liquid water and water vapor diffusivity, ρ_w and ρ_v their density, x_v the water vapor mass fraction in the gas phase, k_w and k_g the liquid water and gas permeability, and μ_w and μ_g the liquid water and gas viscosity. The pressure (P) was calculated from the mass concentration of the gas phase (C_g) using the ideal gas law. In addition, the density of water vapor (ρ_v) was related to its mass concentration (C_v) as follows: