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Sensitivity analysis of parameters affecting the drying behaviour of durum wheat pasta

S. Mercier [a], C. Moresoli [b], S. Villeneuve [c], M. Mondor [c], B. Marcos [a,*]

[a] Université de Sherbrooke, Department of Chemical and Biotechnological Engineering, 2500 Université blvd, Sherbrooke, Quebec, Canada J1K 2R1
[b] University of Waterloo, Department of Chemical Engineering, 200 University Avenue West, Waterloo, Ontario, Canada N2L 3G1
[c] Agriculture and Agri-Food Canada, Food Research and Development Centre, 3600 Casavant Blvd West, Saint-Hyacinthe, Quebec, Canada J2S 8E3

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ABSTRACT

In this work, a comprehensive model of pasta drying combining Neumann boundary conditions, differential shrinkage and with consideration of the constant drying rate period and falling drying rate period was investigated through sensitivity and uncertainty analysis. Results confirmed that shrinkage, moisture loss and drying rate during the constant drying rate period and external resistance to mass transfer did not have a significant impact on the predicted required drying time. The predicted required drying time was influenced predominantly by the effective moisture diffusion coefficient. A correlation to estimate the effective moisture diffusion coefficient was developed from published values and was used to predict the required drying time with an uncertainty of ±3.5 h at a 90% confidence interval. Since this magnitude of uncertainty is unreasonable for most industrial uses, accurate data collection of effective moisture diffusivity should be viewed as a major objective in pasta drying research.

1. Introduction

Multiple studies have shown that the selection of adequate drying conditions is critical for the production of high quality pasta (Manthey and Schorno, 2002; Zweifel et al., 2003; Mercier et al., 2011). However, the selection of adequate drying conditions is generally not a straightforward task. Temperature and relative humidity profiles should be selected carefully such that drying is fast enough to minimize operating time, but sufficiently slow to promote adequate microstructural changes of the starch and proteins (Lamacchia et al., 2007; Petitot et al., 2009; De Noni and Pagani, 2010).

In order to streamline the selection of drying conditions, models have been developed to predict pasta properties during drying without the need to perform costly trial-and-error runs. The first pasta drying model was developed by Andrieu and Stamatopoulos (1986). In their model, the decrease in pasta moisture content is described using a semi-empirical Fick-type law. In the model, moisture transport was assumed to be by diffusion and other mass transport mechanisms were considered to be lumped into the diffusion coefficient. So, the diffusion coefficient is an effective parameter. Using Dirichlet boundary conditions and assuming the effective moisture diffusion coefficient to be independent of the product moisture content, the Fick-type law can be solved analytically. Ponsart et al. (2003), Migliori et al. (2005) and De Temmerman et al. (2007) modified this model by considering the effect of shrinkage on mass transfer, either through one or two-way coupling, and by describing the effective moisture diffusion coefficient as a function of the product moisture content. Ogawa et al. (2012) improved the accuracy of the description of moisture transport at the beginning of the drying process by introducing a constant drying rate period. Although the validity of these models to predict internal moisture profiles remains to be investigated, these models have shown good agreement between the estimated and experimental pasta average moisture content during drying.

The selection of adequate drying conditions should also consider the pasta glass transition. Glass transition represents the transition of amorphous components from a supercooled melt to a glassy state or the opposite (Liu et al., 2006). Pasta undergoes glass transition during drying, which induces important changes in its mechanical, rheological and transport properties. Pasta behaves as a visco-plastic and soft material in the rubbery state and as an elastic and rigid material in the glassy state, with a transition state in between (Rahman, 1995; Cuq et al., 2003). Adequate drying conditions should promote uniform glass transition within the pasta such as to limit internal stresses and the risk of crack formation. The moisture content at which pasta undergoes glass transition can be predicted from the model of Cuq and Icard-Verniere (2001), which was developed from modulated scanning calorimetry measurements.

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* Corresponding author. Tel.: +1 819 821 8000x62166.
E-mail address: bernard.marcos@USherbrooke.ca (B. Marcos).

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Nomenclature

a_w	water activity coefficient (–)
A	drying area (m^2)
Bi_m	mass Biot number (–)
C	concentration ($kg\ m^{-3}$)
D_{eff}	effective moisture diffusion coefficient ($m^2\ s^{-1}$)
DS	mass of pasta dry solid (kg)
E_a	activation energy ($J\ mol^{-1}$)
h_m	surface mass transfer coefficient ($m\ s^{-1}$)
M	pasta moisture content (liquid water + water vapor) on dry basis ($kg\ H_2O\ kg\ dry\ solid^{-1}$)
MW	molecular weight (Dalton)
N	mass flux ($kg\ m^{-2}\ s^{-1}$)
P	pressure (Pa)
r	radial coordinate (m)
R	pasta radius (m)
R_C	drying rate during the constant drying rate period ($kg\ H_2O\ m^{-2}\ s^{-1}$)
R_g	ideal gas constant ($J\ mol^{-1}\ K^{-1}$)
RDT	drying time required to reduce pasta moisture content below 0.1 (d.b.) (s)
RH	relative humidity (%)
Sr	relative sensitivity (–)
t	time (s)
$t_{(1-\alpha)/2,v}$	value of the Student's *t*-distribution for a confidence interval α and a number of degrees of freedom v
T	temperature (K)
T_g	glass transition temperature (K)
V	volume (m^3)
$\%C$	relative moisture lost during the constant drying rate period (%)

Greek symbols

α	confidence interval (–)
β	shrinkage coefficient (–)
ε	porosity (%)
η	volumetric fraction of water lost replaced by air (–)
ρ	density ($kg\ m^{-3}$)
σ	standard deviation
v	number of degrees of freedom

Superscripts

0	reference scenario
ext	external

Subscripts

0	initial condition
$0\rightarrow r$	from the center of the pasta to r
app	apparent
c	critical
DS	dry solid
E	equilibrium
R	at $r = R$
sat	saturation
w	water
∞	in the bulk environment

The selection of adequate pasta drying conditions from mass transfer and glass transition models requires the knowledge of multiple input parameters including pasta thermophysical and geometrical properties, heat and mass transfer coefficients, and initial and boundary conditions. These input parameters can generally be estimated from literature data. However, especially in the food industry, considerable variability is observed for the values reported from different studies. The lack of precision of the parameter estimates can lead to significant uncertainty in the prediction of pasta drying behaviour and glass transition conditions. The quantification of this uncertainty, a prerequisite to confirm the validity of the models, has not been investigated. The aims of this work were to determine the models parameters that influenced predominantly the prediction of pasta required drying time, quantify the uncertainty of the predicted required drying time for relevant industrial processing conditions and evaluate the impact of the uncertainty of the pasta effective moisture diffusion coefficient on the description of pasta glass transition. More specifically, a drying model combining Neumann boundary conditions, differential shrinkage and separation in a constant and a falling drying rate period was first presented and validated with published experimental moisture profiles. The contribution of the major input parameters of this model on the estimates of the drying time was evaluated for a reference scenario. The required drying time predicted according to five published correlations of the effective moisture diffusion coefficient was compared. Estimates of the rubbery, glassy and transition states of pasta according to pasta radial position and drying time were obtained and used to demonstrate the importance of the effective moisture diffusion coefficient correlation. Finally, a new effective moisture diffusion coefficient estimate was established by selecting the average conditions of the five published correlations.

2. Methodology

2.1. Model of moisture mass transfer

A comprehensive model combining Neumann boundary conditions, differential shrinkage and separation in a constant and a falling drying rate period was used in this study for pasta of cylindrical geometry. The following assumptions were made: (1) heat transfer was much faster than mass transfer, such that the difference between the pasta and the bulk air temperature was negligible (Andrieu and Stamatopoulos, 1986; De Temmerman et al., 2007); (2) the moisture transport occurred only in the radial direction because of the large ratio between the pasta length and diameter; (3) the bulk air near the pasta surface behaved as an ideal gas and (4) the longitudinal shrinkage of the pasta was considered negligible.

2.1.1. Constant drying rate period

As proposed by Ogawa et al. (2012), pasta drying was divided in a constant drying rate period and a falling rate period. During the constant drying rate period, the pasta moisture content was described as follows:

$$\frac{d\overline{M}}{dt} = \frac{-R_C A}{DS}, \tag{1}$$

where $\overline{M}$ is the pasta average (averaged according to its radius r) moisture (liquid + vapor) content, t is the time, R_C is the constant drying rate, A is the surface area of the pasta and DS is the dry solids mass content of pasta. During the constant drying rate period, the moisture transport within the pasta is sufficient to maintain saturation at the surface of the pasta. The drying process is mainly controlled by the rate of mass transfer in the gas-phase boundary