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Effect of drying temperature on the rheological characteristics of dried seedless grapes

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ABSTRACT

The grape is the second most widely cultivated fruit in the world after the orange; it is of great commercial interest. The Sultana variety is grown in large quantities in Tunisia and in the Mediterranean countries. The product is easily deformable; the thermo physical properties depend on the water content. By using the static gravimetric method, the sorption isotherms for sultana grapes were determined. By using the experimental drying kinetics and adopting a numerical procedure for solving the Fick's diffusion equation, the mass diffusion coefficient was determined as a function of the temperature and water content of the product. Using the constraint relaxation test, with a texture analysis machine, the mechanical properties of grains of dried grapes were measured. The relaxation function and the Young's modulus were then deduced. These characteristics are key parameters in running simulation models addressing the thermo hydro mechanical behavior and allow the appropriate process and drying time to be subsequently determined in order to avoid unnecessary energy consumption.

1. Introduction

During the drying of food products, the water diffusivity is a crucial parameter for calculating the water transfer inside the product. This coefficient determines largely the water activity on the surface and partly determines the quality of the dried product. Transporting the vapor is a phenomenon that occurs during any drying process. The steam movement is due either to diffusion within the same material, or to convective heat transfer at the surface between the material and its environment. The non-homogeneous distribution of water in the porous solids causes a concentration gradient which initiates mass transport. According to a phenomenological approach, the distribution of water comprises several elementary mechanisms for its transport such as, liquid diffusion, vapor diffusion, diffusion sorption and condensation-evaporation cycles (Karathanos et al., 1990; Kim and Bhowmik, 1995; Xianxi et al., 2012).

The desorption isotherm links the equilibrium moisture content of the solid to the moisture content of the environment, at a given temperature. It is characteristic of many interactions taking place at the microscopic level between the solid skeleton and the water molecules. Therefore, the isotherm allows the behavior of the hygroscopic solid to be described. In fact, the study of the sorption–desorption isotherms is a privileged means of knowledge of the distribution and intensity of water connections in porous media. During these two recent decades, a significant number of works focused on the study of sorption isotherms of food products. The influence of temperature on the isotherms and mathematical models were used to describe them (Iglesias and Cherife, 1976; Cherife, 1983; Labuza et al., 1985; Maroulis et al., 1988; Veltchev and Menko, 2000; Giovanelli et al., 2002).

The majority of works (Roberts et al., 2008; Ortiz-García-Carrasco et al., 2015) used the analytical solution of Fick's law to identify the water diffusivity. This method provides an

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Nomenclature

a_w	water activity
c	concentration ($kg\,m^{-3}$)
ds	dry solid
D	moisture diffusivity (m^2/s)
d	diameter (m)
E	Young's modulus (Pa)
F	force (N)
HR	relative humidity (%)
k_m	mass transfer coefficient ($m\,s^{-1}$)
M_v	vapor molar mass (kg/mol)
m	mass (kg)
P	pressure (Pa)
Re	Reynolds number
R	ideal gas constant ($J\,mol^{-1}\,k^{-1}$)
r	rayon (m)
t	time (s)
T	temperature (°C, K)
Sc	Schmidt number
u	velocity ($m\,s^{-1}$)
V	volume (m^3)
X	moisture content (kg water/kg d s)

Greek symbols

ρ	density ($kg\,m^{-3}$)
μ	dynamic viscosity (kg/ms)
β	shrinkage coefficient
σ	stress (Pa)
τ	relaxation time (s)

Subscripts

0	initial
a	air
l	liquid
s	solid
v	vapor
cal	calculated
eq	equilibrium
exp	experimental
max	maximal
sat	saturated

average value of the diffusivity, which can be considered sufficiently accurate for engineering calculations. However, the applicability of this law is not strictly verified for porous and deformable food. The use of the hypothesis of deformability seems to be appropriate in order to determine the water diffusivity which is water content and temperature dependant. This coefficient describes the internal diffusion phenomenon and is determined during the second phase of the drying kinetics corresponding to the decreasing of the drying rate over time.

Many research studies have applied the numerical method to evaluate the mass diffusion coefficient of various food products (Zogzas and Maroulis, 1996; Esmaiili et al., 2001; Azzouz et al., 2002; Saravacos and Maroulis, 2003; Stamatios and Vassilios, 2004; Doymaz, 2006; Hassini et al., 2007; Inês et al., 2010).

Rheological tests in the food industry have a different role. This tool is used to define a rapid appreciation of product behavior and to determine the parameters that characterize the quality of the dried products on purely conventional criteria. Due to their composition and physico-chemical structure, dry grapes behave as viscoelastic materials (Karathanos et al., 1994; Lewicki and Walter, 1995; Lewicki et al., 1995; Lewicki and Jakubczyk, 2004; Sorvari and Malinen, 2007; Solange et al., 2009; Goksel et al., 2013). A rheological model can be developed based on mechanical tests on materials using a texture-testing machine. The purpose of this research is to examine the rheological characteristics of the dried grapes, in terms of maximal function of compression, stress relaxation as a function of the drying temperature, and Young modulus as a function of moisture content.

2. Moisture diffusion model

In order to identify the water diffusivity of Sultana grapes, as a function of water content, a drying model taking into account the deformable character of the product was developed and numerically solved. The adopted method is based on the minimization of the difference between the calculated and average experimental water content. The range of water content over which water diffusivity is determined must correspond to the falling drying rate period, during which the drying rate is controlled by internal diffusion. Numerous works in the literature used a numerical approach to evaluate the water diffusivity of various food products (Karathanos et al., 1990; Kiranoudis et al., 1995; Lambert et al., 2015).

In order to facilitate the numerical resolution of the equations, the following simplifying assumptions were made:

- The product is biphasic (water–solid)
- Evaporation takes place on the surface
- The shrinkage is ideal and isotropic
- In the initial state, the temperature and humidity of the sample are uniform.

In the case of our material, the liquid (moisture) migrates by diffusion and is conveyed by the shrinking material (Bird et al., 2002). Thus, the conservation equations of the solid and liquid phases are written respectively (Hassini et al., 2007; Ketelaars, 1992):

$$\text{Solid phase}: \quad \frac{\beta}{1+\beta X}\frac{\partial X}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 u_s) - \frac{u_s\beta}{1+\beta X}\frac{\partial X}{\partial r} \tag{1}$$

Liquid phase :

$$\frac{1}{1+\beta X}\frac{\partial X}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\frac{Dr^2}{1+\beta X}\frac{\partial X}{\partial r}\right) - \frac{u_s}{1+\beta X}\frac{\partial X}{\partial r} \tag{2}$$

Eqs. (1) and (2) were numerically solved respectively for u_s and X using the initial and boundary conditions mathematically formulated as follow:

Initial conditions:

$$t = 0: \quad X = X_0, \quad T = T_0, \quad u_s = 0 \tag{3}$$

Boundary conditions:

$$r = 0: \quad \frac{\partial X}{\partial r} = 0, \quad u_s = 0 \tag{4}$$