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Convective drying of a single cherry tomato: Modeling and experimental study

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ABSTRACT

The behavior of peeled and unpeeled cherry tomatoes was investigated during forced convective drying. The study showed that the drying process highly alters the shape of the samples. This alteration (shrinkage) was examined using a non-destructive X-ray microtomography imaging technique. For both cases (peeled and unpeeled tomatoes), the volume of the sample decreased linearly with its moisture content. Furthermore, the effects of the operating air temperature as well as the peel on the drying curves were explored. Accordingly, increasing the air temperature deceased drying time from 1200 ks at 50 °C to 500 ks at 70 °C for the unpeeled sample and from 80 ks at 60 °C to 50 ks at 70 °C for the peeled sample. The effect of the peel was substantial as the drying time of the unpeeled sample was 5–10 times higher than that of the peeled sample. Based on the analytical solution of the diffusion model, a moisture diffusion coefficient was determined using two approaches. The first approach used a graphical representation and the moisture diffusion coefficient was directly deduced from the trend line of the curves. For the second approach, a correction factor was introduced into the analytical solution and the modeling results showed that the moisture diffusion coefficient was varying with the moisture content of the tested material. The comparison between the experimental data and the modeling results using the two approaches showed that the second approach, which included the effect of shrinkage, was more suitable for predicting the variations of the drying curves for the different operating conditions and for both peeled and unpeeled tomatoes. Using this second approach, the moisture diffusion coefficient for the unpeeled tomato was 2.0×10^{-11} m^2/s at 50 °C and 3.5×10^{-11} m^2/s at 70 °C. Similarly, the maximum values of the moisture diffusion coefficient for the peeled tomato varied from 3.0×10^{-10} m^2/s at 50 °C to 5.0×10^{-10} m^2/s at 70 °C. Moreover, performing modeling while neglecting shrinkage resulted in an over estimation of the moisture diffusion coefficient. In addition, operating conditions, dimensions of the samples and shrinkage had a direct effect on the external mass transfer coefficient.

1. Introduction

After potatoes, tomatoes are considered as the second most important produced vegetable crop with a total world production of 162 million tons giving an approximate value of around 80 billion of dollars (FAOSTAT, 2012; Doymaz & Özdemir, 2014). This crop is consumed due to its rich nutritive

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Nomenclature

D	diameter of the material (m)
D_{eff}	moisture diffusion coefficient (m^2/s)
Dv	mass diffusion of the water in the air (m^2/s)
h_m	convective mass transfer coefficient (m/s)
P	pressure (in Pa or bar)
R	radius of the material (m or cm)
R^*	dimensionless radius
S	surface (m^2 or cm^2)
t	time (s)
u	velocity of the air (m/s)
V	volume (m^3 or cm^3)
V^*	dimensionless volume
X	moisture content (kg/kg dry basis)
x_v	molar fraction of water vapor
X^*	dimensionless moisture content
y, r	coordinates

Subscripts

a	dry air
e	equivalent
eq	equilibrium
m	mixed or humid air
v	vapor
sat	saturated
tot	total
0	initial

Greek

ϕ	relative humidity of the air
μ	dynamic viscosity of the mixed air (kg/m s)
ρ	density of the mixed air (kg/m^3)

Dimensionless

Bi	Biot number ($Bi = h_m \cdot R_e/Dv$)
Fo	Fourier number ($Fo = D_{eff} \cdot t/R^2$)
Re	Reynolds number ($Re = u \cdot D \cdot \rho/\mu$)
Sc	Schmidt number ($Sc = \mu/\rho \cdot Dv$)
Sh	Sherwood number ($Sh = h_m \cdot D/Dv$)

values such as carbohydrates and antioxidants, as presented in the study performed by Pinela et al. (2012) for four different Portuguese tomatoes. Branthome (2010) reported that around 70% of the total production, representing more than a hundred million tons of tomatoes is consumed in its fresh state and 30% (more than 48 million tons) after processing. Dewanto et al. (2002) showed, in their study, that applying thermal processing increased the antioxidant activity of tomatoes. Usually processing generates by-products in form of wastes, pomace or peels. El Badrawy and Sello (2011) showed that tomato peels are an excellent source of carbohydrates, proteins, minerals and other components.

It is well known that tomatoes contain a high level of moisture, making it a perishable material that needs processing for its preservation or storage. Drying is the most common process used for these purposes. Depending on the industrial application, usually, before drying, tomatoes are peeled and seeds are removed and cut into small slices, halves or dices. In addition to the time consuming nature of these operations, removing the peels (presented as a valuable part of the product, El Badrawy and Sello, 2011) reduces the nutritional value of the tomato and increases the wastes coming from food products. Several studies were developed in order to deliver better fundamental and practical understanding of tomato drying. Doymaz and Özdemir (2014) presented the effect of the operating parameters, in particular the temperature of the drying air and the thickness of the tested material, on the tomato behavior during convective drying. A particular care was given to the effect of the pre-treatment on the drying curves, the diffusion coefficient, and the rehydration rate. The authors (Doymaz and Özdemir, 2014) found that tomato drying was highly affected by the cited parameters. The effect of the drying air temperature on the tomato drying kinetics during convective drying and the influence of introducing salting were investigated by Xanthopoulos et al. (2012a). The drying parameters, such as the diffusion coefficient were presented as a function of temperature. The authors show that for both cases (with and without salt), the drying curves did not show a constant drying rate phase. However, the drying time was reduced by 5 h due to salt introduction. It is important to note that in several published studies (Doymaz and Özdemir, 2014; Xanthopoulos et al., 2012a; Demiray and Tuleh, 2012; Gaware et al., 2010; Doymaz, 2007 are given as examples), the shrinkage phenomenon that occurs during drying was not included in the mathematical modeling of the process. According to recently published studies, ignoring this phenomenon during modeling, can bring to an over estimation of the drying parameters (Li et al., 2014; Bennamoun et al., 2013a, 2013b; Rahman and Kumar, 2011). A more appropriate mathematical model was developed by Hossain and Gottschalk (2009) for a single layer of tomato. In their model "shrinkage" (according to the applied drying conditions) was investigated and introduced as part of the diffusion model. Xanthopoulos et al. (2012b) performed numerical simulation of tomatoes and showed the influence of shrinkage on both peeled and unpeeled tomatoes. At the end of the process, the shrinkage was 70% for the unpeeled tomato and around 85% for the peeled tomato. The diffusion coefficient was determined and presented as a function of the drying conditions. Moreover, the diffusion coefficient was higher for the peeled tomato. Other innovative methods such as application of microwave and infrared techniques were also investigated. Doymaz, 2014 studied the effect of the power of the infrared source on the drying curves, the drying kinetics, diffusion coefficient and rehydration of the tomato. Accordingly, the diffusion coefficient was presented as a function of the power level of the energy source. The author found that increasing the power level lead to a shorter process. Similar observations were obtained by Tilahun and Oke (2013) and Abano et al. (2012), using novel techniques with respectively a combination of microwave – hot air and microwave – vacuum drying of tomatoes. In both cases, the authors determined the diffusion coefficient and presented it as a function of the power level of the heating source. The comparison between the radiative and the convective drying methods was favorable to the radiative methods with a much shorter drying time.

The purpose of this work is to investigate forced convective drying of a single cherry tomato with special care given to the shrinkage phenomenon determined using x-rays imaging analysis. Based on the diffusion model, with respect to the operating drying conditions, two approaches are then proposed and their results compared. The study was developed for both peeled and unpeeled cherry tomatoes. It gives practical information (which can be easily exploited by industries)