Industrial Crops & Products xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

Developing predictive models for determining physical properties of coffee beans during the roasting process

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ARTICLE INFO

Keywords:
Bean density
Quality
X-ray microtomography
Mass loss

ABSTRACT

This study aims to evaluate and model the variation in the physical properties of coffee beans in isothermal roasting conditions, providing mathematical expressions that can be used for heat and mass transfer models for coffee roasting. Arabica coffee beans were studied with an initial moisture content of 0.129 $kg_w\,kg_{dm}^{-1}$ and roasted in a direct gas burning roaster. Five temperatures were set inside the cylinder (200, 220, 240, 260 and 280 °C). The beans were roasted uniformly by suspension in the center of the drum. A thermocouple recorded the temperature every 5 s. X-ray microtomography was used to analyze the evolution of the internal matrix during the roasting process. The moisture content and physical properties (volume, surface area, and density) of each coffee bean were evaluated every 20 s. Empirical models were fitted to represent the physical properties as a function of the moisture content. It was observed that the volumetric expansion is isotropic at roasting temperatures above 220 °C. The final bean volume can reach up to 1.8 times the initial volume. The bean density varied linearly with the moisture content, presenting a larger drop at a higher roasting temperature.

1. Introduction

During the roasting process, the coffee bean is subjected to high temperatures, resulting in physical-chemical changes in its structure. Initially, at temperatures below 160 °C, drying occurs in which the coffee bean dehydrates, releasing steam and initiating the expansion of the solid matrix. When the coffee bean reaches temperatures above 180 °C, an exothermic reaction involving polysaccharides, proteins, chlorogenic acid, and trigonelline begins to form the compounds responsible for the color, flavor, and aroma of roasted coffee beans (Hernández et al., 2008; Bottazzi et al., 2012). In this second stage, CO_2 is released as the product of the reaction, contributing to the matrix expansion (Schenker, 2000).

The expansion mechanism can be studied as a balanced case of the formation of water vapor and CO_2 as the driving force and the state transitions of the cell wall material as the resisting force (Geiger, 2004). Schenker (2000) observed that glassy state transitions stretch during roasting, finding that the coffee bean remains for a long time in the elastic state during roasting at high temperatures, which contributes to a high expansion capacity under these conditions. Coffee roasted at high temperatures has high volumetric expansion, an increased mass loss, and large pores, facilitating the migration of oil and CO_2; this increases the likelihood of rust during storage (Schenker et al., 2000; Geiger, 2004; Franca et al., 2009; Wang and Lim, 2014a).

The release of water vapor and CO_2 account for the majority of the mass loss of the bean during roasting. This and the change in coffee bean color is the main parameter to determine the end of the process and the desired degree of roasting (Fabbri et al., 2011). The density of the roasted bean is related to the amount of mass lost in the process. A higher density indicates a high-quality coffee bean. In Brazil, in most cases, the roaster operator defines the degree of roasting based on coffee bean color. Nonetheless, this practice can lead to errors, as observation is subjective and the color inside the coffee bean can be different from the color on the surface (Hernández et al., 2008). Franca et al. (2009) concluded that color and weight loss alone are not reliable as roasting degree assessment criteria and that roasting temperature must also be taken into account.

During the last years, several studies have tried to develop process

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https://doi.org/10.1016/j.indcrop.2017.12.015
Received 1 September 2017; Received in revised form 24 October 2017; Accepted 5 December 2017
0926-6690/

Fig. 1. Direct gas burning roaster (brand Rod Bel, 4 burners).

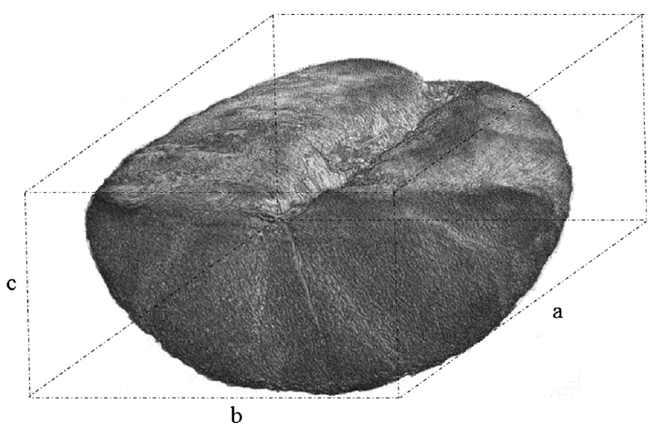

Fig. 2. Semi-ellipsoid approximation for the coffee bean.

Table 1
Estimated parameters for the Copace-volume model for the volumetric expansion ratio, coefficient of determination (R^2), standard deviation of the estimate (SDE) and mean relative error (MRE).

Model	T_a (°C)	α	β	MRE (%)	SDE (% d.b.)	R^2
Copace-volume	200	−5.57	19.74	2.15	0.041	0.971
	220	−6.12	22.58	2.25	0.045	0.974
	240	−7.34	32.42	2.59	0.054	0.961
	260	−7.87	35.52	2.87	0.069	0.934
	280	−8.43	40.07	1.30	0.032	0.986

control tools for on-line monitoring. This control can be made by monitoring and estimating the bean temperature (Basile and Kikic, 2009; Fabbri et al., 2011; Bottazzi et al., 2012; Alonso-Torres et al., 2013) and by monitoring the volatile compounds generated during the process.

Approximately 800 volatile compounds have been identified in roasted coffee and about 40 of them are responsible for aroma (Belitz et al., 2009). Its presence and intensity in the final product depends on the time-temperature binomial during roasting and is an index of quality. Its monitoring is done using techniques of laser ionization and mass spectrometry (Dorfner et al., 2004; Wieland et al., 2012; Hertz-Schünemann et al., 2013; Gloess et al., 2014).

At the end of the roasting process, the beans must be cooled to ensure that the exothermic reaction stops to avoid over-roasting. The cooling must be fast, so it is done using forced air convection. The efficiency of this process depends on the properties of the coffee bean. High porosity implies a high surface area available for thermal

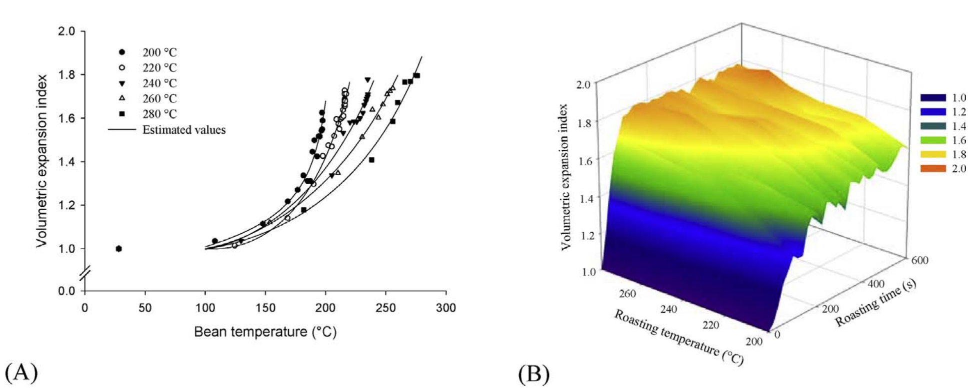

Fig. 3. Volumetric expansion index of coffee bean (A) according to the bean temperature for different roasting temperatures, and as a function of temperature and process time (B).