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Research Paper

Drying rate control in microwave assisted processing of sliced apples

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The most enhanced microwave systems for the preparation of quality-dehydrated fruits continuously adjust the power level in order to maintain the product temperature above a target value. As a result, typical drying curves that exhibit high drying rates in the middle stage are obtained. This can often lead to quality damage or undesirable changes on food colour and texture. In response to these issues, a microwave system is proposed that can realise drying processes keeping drying rates constant. This approach required a continuous temperature adjustment of the apple slices under test, whose temperature was detected by a computer-aided infrared thermography system. Since temperature corrections were required only during the middle stage of the process, the overall drying time was only slightly affected by the proposed control strategy. Nevertheless, compared to microwave drying with different constant temperatures (60, 70 and 80 °C), the resultant benefits of operating at constant drying rates included an improvement of texture and rehydration properties. No differences in colour of sliced apples were observed.

1. Introduction

Over recent decades, attractive results arising from microwave heating have led to the development of several techniques to control the magnetron-delivered power. Microwave (MW) assisted drying under appropriate processing conditions can increase speed of operation and improve fruit quality, such as colour and texture (Gunasekaran, 1999). Researchers have studied various methods in order to control MW power level aiming to meet consumer expectations in term of high quality food products. Thus, intermittent and continuous methods were proposed, most of them based on keeping power density or temperature under control (Cuccurullo, Giordano, Metallo, & Cinquanta, 2017; Li, Wang, Raghavan, & Cheng, 2006).

It is well known that operating at constant power rates lead to unwanted temperature increases in the early stage, and may cause undesirable changes in quality, such as browning of the fruit surface and charring (Raghavan, Li, Wang, & Gariépy, 2010; Li, Raghavan, & Wang, 2010a). According to Clark (1996) and Nijhuis et al. (1998), excessive temperatures at the edges and corners of products may lead to overheating and irreversible drying-out, possibly resulting in scorching.

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Symbols and abbreviations

Symbol or abbreviation (Unit) & Meaning

MW	microwave
IR	infrared
RMSE	root mean square error
d.b.	dry basis
i.d.	internal diameter
o.d.	outside diameter
w	water
$M_d(t)$ (–)	moisture content on dry basis
$m_w(t)$ (kg)	moisture content at time t
m_d (kg)	dry mass
$DR(t)$ (s^{-1})	drying rate
DR_{max}(s^{-1})	target value for $DR(t)$
a (s^{-1})	equation fitting coefficient
b (s^{-c-1})	equation fitting coefficient
c (–)	equation fitting coefficient
d (s^{-e})	equation fitting coefficient
e (–)	equation fitting coefficient
$\Gamma(\beta, z) = \int_z^\infty t^{\beta-1}e^{-t}dt$	incomplete gamma function
T_{max} [°C]	maximum surface temperature
t_c (s)	characteristic time for which $M_d = 0.8$
NEB (abs (absorbance))	non-enzymatic browning
$WI = 100 - \sqrt{(100 - L)\hat{}(2) + a\hat{}(2) + b\hat{}(2)}$	white index
L*	brightness
a*	red index
b*	yellow index
PPO	polyphenol oxidase

Heating fruit at constant temperature usually implies a typical drying curve with three drying periods (Zhang, Tang, Mujumdar, & Wang, 2006): I) heating-up period, in which the temperature of the product increases with time and the material starts to lose moisture at relatively low rates; II) constant drying rate period, during which a stable temperature profile is established and drying rates are highest; III) falling rate period, during which drying rates progressively slow down. Some authors have reported that the period of constant rate drying was scarcely observed under all drying conditions during MW-driven heating (Cuccurullo et al., 2017; Maskan, 2000; Wang, Xiong, & Yu, 2004). One of the major disadvantages of this control strategy was that too rapid mass transport caused quality damage or undesirable changes in food texture (Koné et al., 2013; Martynenko & Janaszek, 2014). Therefore, a suitable and adjustable temperature level or energy density should be set in order to meet key requirements for product quality, time and energy consumption. In this framework, Li, Raghavan, Wang, and Vigneault (2011) developed a microwave drying system that allowed the drying curve in the middle stage to be linearised; to this end, the power level was varied so as to reduce product temperature, which was recorded online using a fibre optic sensor. An evolution of this system was based on a fuzzy logic control, able to adjust the drying curves during heating (Li, Raghavan, & Orsat, 2010b; Li et al., 2010a; Raghavan et al., 2010).

In the present paper, a control system able to slow down the drying rate in the middle stage of the drying process was proposed in order to keep the drying rate at a constant value. The system adjusted the operating temperature level continuously, depending on the actual moisture content of the apples slices under test. For this an infrared camera looking at the surface temperatures of the apple slices was used to set the magnetron-delivered power. Then, a relationship between temperature, drying rate and moisture content of the samples was established by suitable data processing, based on a preliminary characterisation of different drying kinetics. Moreover, an empirical model was proposed which fits the experimental data along all the stages of the drying process, whereas typical data fitting only involves the falling rate period. Finally, the quality of the dried apples was assessed by colour and texture analysis, as well as by rehydration capacity.

2. Materials and method

2.1. Microwave prototype

Drying experiments were carried out using a Lab scale MW plant (Fig. 1) housing a magnetron with a nominal power output of 2 kW. The magnetron operated at 2.45 GHz. The reverberating chamber was a cubic metallic room (1 m^3) equipped with a fan at the bottom of the cavity for continuous air renewal. Fresh air was introduced into the chamber at room conditions (50 ± 5% RH, 24 ± 1 °C) and constant volumetric rate (108 m^3 h^{-1}). A rotating mode stirrer was placed inside the oven to improve heating uniformity (Cuccurullo et al., 2017; Li et al., 2010b). A teflon annulus (500 mm i.d., 550 mm o.d.) was covered with a high-density polyethylene squared grid (10 mm × 10 mm) to realise a turntable carrying the test samples. The angular velocities were 7 and 10 rpm for the turntable and the stirrer, respectively. The grid was connected to a technical balance (Gibertini EU-C 1200 RS, Novate Milanese, Italy) located on the top of the oven for online measurement of moisture loss; the acquisition rate was 120 samples per minute.

An infrared (IR) thermometry system (ThermaCAM Flir P65, Canada) to monitor the surface temperatures of the samples was installed on the oven top surface; it looked inside the reverberating chamber through a square hole (70 mm × 70 mm). The hole was properly shielded with a metallic grid, which allowed the IR radiation from the detected scene to escape but entrapped the microwaves. A specifically realised LabView® software was employed to acquire the feedback signal produced every 0.9 s by the IR equipment. The code then authorised on/off switching of the magnetron-delivered power through an I/O board (AT MIO 16XE50, National Instruments, Assago, Italy). The actual temperature level was then adjusted according to the moisture ratio measurements (see Section 2.3).

2.2. Sample preparation

Fresh apples (*Golden delicious*) were purchased from a local market and stored at 4 °C before drying. Apples were cut into slices (10 ± 0.2 mm thick, 20 ± 0.3 mm diameter) using a sharp