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Research Paper

Temperature gradient control during microwave combined with hot air drying

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Fresh carrot cubes were blanched and dried by microwave processing combined with hot air drying. Material temperature, temperature difference and size of cube were optimised in terms of total vitamin C content, colour change, drying time, sensory evaluation and rehydration ratio of dried samples. During a stage under the optimal drying condition, drying rate was affected by temperature gradient, as evidenced by changed shrinkage. The effect of different temperature gradients on the drying rate and quality was compared with that under the optimal condition by using fitted shrinkage models of the optimised material temperature, temperature difference and size of cube. The quality of dried carrot cubes under the average temperature gradient (ATG) of 6 °C mm^{-1} was better than that under other ATGs. A simple linear control method was developed based on the control for industrial production. Results showed that the product quality and drying time of samples in linear control were similar to those dried at 6 °C mm^{-1}.

1. Introduction

Carrot is highly nutritious because it contains vitamins C and various minerals. Vitamin C influences most damaging radical species produced in the human body.

Microwave drying is an efficient method that involves high drying rates, high energy efficiency and improved product quality (Al Juhaimi et al., 2016; Apaolaza, Valat, Ginisty, Sommier, & Jomaa, 2015; Cao et al., 2016; da Silva et al., 2016; Sharifian, Nikbakht, Arefi, & Motlagh, 2015; Skoneczna-Luczkow & Ciesielczyk, 2016). In microwave drying of food materials, the core temperature is usually higher than the surface temperature, and the internal water is pumped outwards (Schiffmann, 1995). This mechanism also creates porous structure in the food material, facilitating water vapour transport and speeding up the drying process (Drouzas, Tsami, & Saravacos, 1999). Convective drying is more efficient than microwave drying for removing free water on and near the surface (Alibas, 2007), but its case-hardening effect may prevent further evaporation of water from inside

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Abbreviations

MHAD	microwave combined with hot air drying
T_m (°C)	material temperature
ΔT (°C)	temperature difference
D (mm)	size of cube
ATG (°C mm^{-1})	average temperature gradient
RSM	response surface methodology
MC	moisture content

(Gulati & Datta, 2015; Kumar, Millar, & Karim, 2014). The combination of these two methods in numerous practical studies demonstrates efficiency, economy and in some cases, good product quality (Albanese, Cinquanta, Cuccurullo, & Di Matteo, 2013; Kumar, Prasad, & Murthy, 2014; Prabhanjan, Ramaswamy, & Raghavan, 1995; Ratanawilai, Nuntadusit, & Promtong, 2015; Talens, Arboleya, Castro-Giraldez, & Fito, 2017; Yu, Zuo, & Xie, 2015a, 2015b; Zhao et al., 2014). To accelerate the drying process, microwave drying requires a large temperature difference between the core and surface to enhance its pumping mechanism, resulting in a high core temperature and a low surface temperature. However, a large temperature difference may also pump out useful nutrients through very large pores, leading to poor product quality (Torringa, Esveld, Scheewe, van den Berg, & Bartels, 2001). The convective drying mechanism also demands a relatively high surface temperature to expedite surface water evaporation. Therefore, a moderate temperature difference between the core and surface of food materials is preferred. Compromising and optimising the two different energy sources are suggested. In the literature, only one study reported on this topic. Song, Li, and Raghavan (2017) investigated the influence systematically by using a drying system with feedback control of the two temperatures. However, this study neglected one important factor, namely, shrinkage of the food materials during drying. The volumetric change in food can reach 65% from beginning to end, depending on the type of food and the drying conditions (Arevalo-Pinedo, Murr, Arevalo, & Giraldo-Zuniga, 2010; Hatamipour & Mowla, 2002; Nahimana, Mujumdar, & Zhang, 2011; Nahimana & Zhang, 2011). If a fixed temperature difference between the core temperature (i.e. dominated by microwave energy) and surface temperature (i.e. in equilibrium with the surrounding hot air temperature) is applied in the entire drying process, the average temperature gradient (ATG) will increase greatly as the drying proceeds. Andres, Bilbao, and Fito (2004) reported a high drying rate in a stage in microwave combined with hot air drying (MHAD). The acceleration of the drying rate can be explained by the simultaneous action of temperature and moisture content (MC) gradients (Constant, Moyne, & Perre, 1996). Other studies reported similar results, but detailed analysis was not performed (Andres et al., 2004; Varith, Dijkanarukkul, Achariyaviriya, & Achariyaviriya, 2007). Considering that temperature gradient plays an important role, research is needed on temperature variance control in the study of MHAD.

Material temperature (T_m), temperature difference (ΔT) and size of cube (*D*) are three factors employed in response surface methodology (RSM) to optimise the drying conditions for carrot cubes. Mathematical models of shrinkage were built based on the optimised conditions. ATG exerts important effects on the drying process; as such, properly changing the temperature difference using a shrinkage model in different drying stages is a potential solution to optimise the drying process (Song et al., 2017).

This study developed a new MHAD system that can automatically and continuously adjust the power levels of a microwave oven and hot air generator, control the product temperature and temperature of hot air and measure the mass of samples online. The specific objectives of current work are:

1) To design and build a microwave combined with hot air dryer and test the system;
2) To determine the optimum drying condition through RSM;
3) To establish a shrinkage mathematical model based on the optimal condition;
4) To study the effect of average temperature gradient on the drying kinetics;
5) To develop a simplified temperature control method without mass measurement.

2. Materials and methods

2.1. Materials

Fresh carrot was procured from the local market of Wuxi, Jiangsu (China) and stored in a refrigerator at 4 °C. The carrots were washed, peeled, cut into uniform cubes of 8 mm × 8 mm × 8 mm, 10.82 mm × 10.82 mm × 10.82 mm, 13 mm × 13 mm × 13 mm and 18 mm × 18 mm × 18 mm by using a set of kitchen slider (knives) (LH-200, Zhuorui, Cangzhou, China). Prior experiments had showed that for size of cube less than 8 mm, the core temperature of the sample was the same as its surface temperature, with uniform temperature distribution within the sample. However, for size of cube more than 8 mm, temperature gradient developed along the thickness of the sample. The samples were blanched in hot water at 95 °C for 5 min (Huang, Zhang, Adhikari, & Yang, 2016) and immediately cooled in chilled water to avoid overprocessing. The initial MC of the blanched samples was 11.998 g g^{-1} (d.b., dry basis). In brief, 20 ± 1 g of the samples were used in each experiment and dried to approximately 0.11 (d.b.). The average result of three replications was used for analysis.

2.2. MHAD system

A 2450 MHz microwave oven (MM720KG1-PW, Midea, Foshan, China) and a hot air generator (850, Kada, Foshan, China) were modified and assembled as microwave dryer. The schematic of the system is shown in Fig. 1.

2.2.1. Microwave drying unit

The power supply to the magnetron was controlled with the DAQ board (USB6259, National Instrument, TX, USA) and executed with another control circuit (220 V). Product