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A novel method to improve heating uniformity in mid-high moisture potato starch with radio frequency assisted treatment

Hankun Zhu [a], Dong Li [a], Shujun Li [a, b, *], Shaojin Wang [c, d, **]

[a] College of Engineering, China Agricultural University, Beijing, 100083, China
[b] Chinese Academy of Agricultural Mechanization Sciences, Beijing, 100083, China
[c] College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling, Shaanxi, 712100, China
[d] Washington State University, Department of Biological Systems Engineering, Pullman, WA, 99164-6120, USA

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An alternative method to improve treatment efficiency for industrial applications of mid-high moisture potato starch was explored based on radio frequency (RF) heating, but the large cold spot area during RF treatment was the biggest obstacle for technology development. The purpose of this study was to develop a new method to reduce the cold spot area and improve RF heating uniformity for mid-high moisture potato starch by modifying the electromagnetic field distribution in the sample with a Electromagnetic Wave Conductor (EWC). The simulation model of RF heating was established to study the temperature distribution using commercial COMSOL software. Dielectric properties of potato starch with moisture content of 31.55% w.b. were measured for computer simulation, and the associated RF experiments were conducted as the validation of the EWC method. The results showed that the parameters of EWC (width and height) had a positive correlation with the RF heating uniformity. The improved target uniformity index (TUI) and the decreased heating time indicated significant effects of EWC. Finally, optimizing EWC parameter equations were developed and could be used for improving RF heating uniformity in future applications.

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1. Introduction

Mid-high moisture content (20%–50% wet basis) food materials are a large category, basically including raw, fresh, mashed and semi-finished foodstuff. Native starch is a good texture stabilizer and regulator in food systems and could be used for preparing different products (Ruan et al., 2009). Potato ranks fourth after wheat, rice and corn in production worldwide and a new potato staple food development plan has just been announced by Ministry of Agriculture in China (Lu, 2015). Industrial processing of potato starch includes washing, rasping, screening, filtering and drying. The starch with moisture content of about 30–40% w.b. after filtering needs to be dried to around 17% w.b. for safe storage in the drying process, which is commonly completed by hot air dryer (Talburt and Smith, 1987). In potato processing, traditional drying methods (hot air and drum dryer) with high temperatures result in high energy consumption, low heating efficiency and high production costs (Aviara et al., 2014; Gowda et al., 1991) with negative effects on the functions of starch (Bo and Tunde, 2013). Therefore, it is important to explore an alternative advanced drying or processing method to achieve high efficiency and product quality with low cost.

Electromagnetic energy has been proposed as a new alternative treatment method for agricultural product processing due to its fast and volumetric heating (Jiao et al., 2014; Wang and Tang, 2001). Radio frequency (RF) energy is a kind of electromagnetic wave for frequencies between 1 and 300 MHz, and has been widely used in baking (Koral, 2004), drying (Wang et al., 2011), pasteurization (Liu et al., 2011) and disinfestations (Wang et al., 2010) with high penetration depth and easy temperature control as compared to microwave heating (Wang et al., 2011). The major problem of RF treatments is the poor heating uniformity, especially for the

* Corresponding author. College of Engineering, China Agricultural University, Beijing, 100083, China.
** Corresponding author. College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling, Shaanxi, 712100, China.
E-mail addresses: lisj@caams.org.cn (S. Li), shaojinwang@nwsuaf.edu.cn (S. Wang).

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samples with higher moisture content (Huang et al., 2016).

Many studies have been carried out to improve the RF heating uniformity. For example, Birla et al. (2004) developed a fruit mover with pumped water to improve the RF heating uniformity of fresh fruit. Jiao et al. (2015) found that the similar dielectric constant surrounding material (polyetherimide, PEI) of the sample container is effective for the RF heating uniformity improvement in peanut butter. Huang et al. (2016) used polystyrene as a container material for dry soybeans to improve heating uniformity and studied the influence of container thickness on temperature distributions using computer simulation models. However, these methods are limited to dry food materials. It's desirable to study some new and practical methods for improving RF heating uniformity in potato starch with mid-high moisture content.

Based on the RF electromagnetic field distribution and bending characteristics (Birla et al., 2004), the problem of RF heating uniformity is mainly caused by the non-uniform electromagnetic distribution in the material and surrounding space, especially for the dielectric materials with higher moisture content (Birla et al., 2008; Farag et al., 2010; Tiwari et al., 2011). To improve the RF heating uniformity over the whole volume, the areas with less electromagnetic intensity need to introduce more energy by a conductor. Based on the electric force line bending theory between medias with different dielectric properties (TEC, 1987), the so-called electromagnetic wave conductor (EWC) with lower dielectric loss factor is introduced and placed inside the food sample to check if the RF heating uniformity could be improved.

The objectives of this study were 1) to measure the dielectric properties of potato starch with mid-high moisture content for computer simulation, 2) to establish RF heating simulation model of the sample with EWC, 3) to evaluate the heating uniformity and rate as influenced by EWC with different size, and 4) to optimize the EWC parameters (height and width) for achieving a uniform and efficient RF processing.

2. Materials and methods

2.1. Sample preparation

Standard refined potato starch (Maoyuan Inc., Pingliang, Gansu, China) was used in this study with the initial moisture content of 14.4% w.b. determined by standard oven method (SAC, 1985). In most of the potato starch industry, the moisture level of original materials in drying and modified starch processing is around 20%–40% (Sajilata et al., 2006; Zavareze et al., 2010). In this study, the moisture content of starch sample was adjusted to around 30% w.b. by adding predetermined quantity of distilled water. The preconditioned samples were gently mixed and shaken manually for 15 min. The samples were sealed in an isolated air-tight plastic bag at 4 °C for 4 d in a refrigerator to balance the moisture, and the bags were shaken 3 times per day during storage. The sample bags were taken out from the refrigerator after equilibrium and put in an incubator (BSC-150, Shanghai BoXun Industrial & Commerce Co., LTD., Shanghai, China) at 23 °C for one more day to obtain uniform initial sample temperature before the experiment (Huang et al., 2016; Wang et al., 2015b). The final moisture content of the adjusted starch was 31.55% w.b. for dielectric properties measurement and RF treatments.

2.2. Dielectric properties measurement with physical properties

The open-ended coaxial probe technique is a popular method for measuring dielectric properties and usually used for liquid or semi-solid materials over a broad frequency range. In this study, potato starch was compressed into cylindrical samples by a stainless steel cylindrical holder (diameter 21 mm and height 85 mm) and contacted tightly with the probe (Guo et al., 2010; Ling et al., 2014; Zhang et al., 2016). Dielectric properties measurement system consisted of an Agilent 85070E open-ended coaxial probe, an Agilent E4991B vector impedance analyzer (Agilent technologies, California, U.S.A.), and a computer with 85070E dielectric probe kit software (Agilent technologies, California, U.S.A.). The sample was confined in the cylindrical holder with a spring to ensure a close contact between the tip of the coaxial probe and the sample during the measurements. The sample temperature was controlled by circulating oil from an oil bath (LNEYA SST-20, Wuxi Guanya Constant Temperature Cooling Technology Co., Ltd., Wuxi, China) into the jacket of the test holder. The sample center temperature during measurement was monitored by a thermocouple (HH-25TC, Type-T, OMEGA Engineering Inc., Stamford, Connecticut, USA) to reach 4 selected measuring temperatures (30, 40, 50, and 60 °C), which were based on the safe temperature to protect starch quality (Çatal and İbanoğlu, 2012). Measurements of starch dielectric properties were conducted in two replicates at each selected temperature. Before the measurement, the analyzer was turned on for about 30 min for warming up and then calibrated with open, short and 50 Ω load in sequence. The open-ended coaxial probe and coaxial-cable were then attached to the system, and further calibrated with air, short probe, and 25 °C distilled water.

Bulk density of potato starch with moisture content of 31.55% w.b. at room temperature was measured by a basic volume method with a 132 × 184 × 64 mm^3 polypropylene rectangular container and determined to be 770 ± 2 kg m^{-3} based on three replicate measurements. Thermal conductivity and heat capacity of potato starch sample were 0.3247 W $m^{-1}k^{-1}$ and 2350 J kg^{-1} K^{-1} at the 45 °C based on the study of Ryynänen (1995) and Noel and Ring (1992), respectively. Table 1 lists physical properties of the container, and surrounding materials, including polystyrene (EWC), polypropylene (container), aluminum (RF system), and air, for computer simulation.

2.3. Determination of EWC

In RF heating for bulk materials, non-uniform electromagnetic

Table 1
Electrical and physical properties of polystyrene, polypropylene, air, and aluminum used in simulation modelling.

Container and surrounding material	Density (kg m^{-3})	Thermal conductivity (W m^{-1} K^{-1})	Heat capacity (J kg^{-1} K^{-1})	Dielectric constant (ε')	Loss factor (ε'')
Polystyrene	25[a]	0.036[a]	1300[a]	2.6[b]	0.0003[b]
Polypropylene[c]	900	0.26	1800	2.0	0.0023
Air[d]	1.2	0.025	1200	1	0
Aluminum[d]	2700	160	900	1	0

[a] Juran (1991).
[b] Brandrup et al. (1989).
[c] Von Hippel (1954).
[d] COMSOL material library (2012).

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