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An improvement in the immersion freezing process for frozen dough via ultrasound irradiation

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ABSTRACT

The ultrasound-assisted freezing (UAF) process, the influence of UAF on the quality and microstructure of frozen dough, were investigated. Dough cylinders were immersion frozen in an ultrasonic bath with 25 kHz frequency and five different power levels. The results showed that UAF process was consists of three stages: a liquid-state temperature decrease stage, a phase-transition stage, and a solid-state temperature decrease stage; ultrasound enhanced heat transfer more efficiently in the latter two stages than in the first stage, due to more heat generation in the first stage. At 288 or 360 W power levels, the total time for dough freezing shortened more than 11% significantly ($P < 0.05$), and the required time for each stage was reduced. Moreover, crystal nucleation was also enhanced by ultrasound with the formation of a large number of tiny ice crystals inside the frozen dough, and the maximum penetration force of ultrasound-assisted frozen dough increased.

1. Introduction

The expansion pressures generated by the large ice crystals which are formed during food-freezing and freezing-storage processes may damage the food structure and lead to a deterioration in the structure of the frozen food (Inoue et al., 1994; Rasanen et al., 1995). Presently, efforts, such as shortening the freezing period, increasing the freezing rate and maintaining temperature stability during freeze-storage, are being made to optimize important factors that diminish the influence of large ice crystals on food quality. New techniques have been developed in food freezing, such as high-pressure food freezing (Fuchigami et al., 1998), application of ice nucleation active bacteria (Li and Sun, 2002a; Widehem and Cochet, 2003), biological freezing protein technique (Zasypkin and Lee, 1999), Cell Alive System (CAS) technology (http://www.a-interview.com/en/world/item/92.html), superchilling technology (Kaale et al., 2011), and ultrasound-assisted food freezing (Zheng and Sun, 2006).

Power ultrasound, with high energy and low frequency in the kHz range, can exert ultrasonic cavitation, mechanical and thermal effects on chemical and structure make-up of the food, as well as cause a series of secondary effects, such as shock waves and micro-jets. Utilization of power ultrasound in food processing, preservation and extraction is a green novel technology (Chemat et al., 2011). Ultrasound-assisted freezing (UAF) can improve the quality of frozen food without the need for additional additives, which is in line with the developing trend in the modern green food industry, and it could have promising applications in freezing of foods (Kiani et al., 2012; Saclier et al., 2010). Ultrasound cavitation can induce primary ice nucleation by the cavitation bubble collapses or movements, and promote secondary ice nucleation by breaking up the pre-existing dendritic ice crystals into smaller fragments to produce the smaller crystals with greater size uniformity (Chow et al., 2003, 2004, 2005; Delgado et al., 2009; Delgado and Sun, 2011; Inada et al., 2001; Kiani et al., 2011, 2012; Petzold and Aguilera, 2009; Saclier et al., 2010; Zhang et al., 2001, 2003; Zheng and Sun, 2006), so that the quality of frozen food can be improved during the UAF process. It has been reported that freezing under the ultrasound irradiation at 25 kHz frequency did less damage to potato cells and facilitated a better preservation of cell structure in comparison with traditional food-freezing techniques (Li and Sun, 2002b; Zheng and Sun, 2006). Microstructures with small and uniform ice crystals have been determined in ultrasound-assisted frozen wet gluten to beneficially reduce the deterioration of the gluten network and improve its quality (Song et al., 2009). Although power ultrasound was recognized to enhance convection of heat transfer by acoustic cavitation or acoustic streaming (Legay

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Abbreviations: BU, Brabender units; FTA, food texture analysis; SEM, scanning electron microscopy; UAF, Ultrasound-assisted freezing.

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et al., 2011), these previous studies have focused mostly on the impacts of ultrasound on ice crystallization with little attention to the heat-transfer effect during the UAF process.

In this paper dough was used as the experimental material to investigate the influence of ultrasound on freezing efficiency because of the extensive use in the food industry and easy moldition into a uniform shape which can eliminate the interference of food shape in the experiments. Dough cylinders were immersion frozen in an ultrasonic bath system, in which ultrasound was applied intermittently with 30 s on/30 s off duty cycle at 25 kHz frequency and at five different power levels (175-, 224-, 288-, 360-, or 418-W). The properties of ultrasound-assisted frozen dough were monitored via food texture analysis (FTA).

2. Materials and methods

2.1. Wheat flour processing

High-grade bread flour (Guangdong Baiyan Grain and Oil Industrial Co., Ltd., Guangzhou, China) was used in this study. The protein and moisture contents of this flour were measured with the results of 13.3% protein content and 13.2% moisture using the Dumas combustion method [Nitrogen Autoanalyzer (Tru Spec N, LECO, USA)] and HB4-3 rapid water content determination (Mettler-Toledo, Switzerland) respectively. A 300 g kneading-through (mixer) was used for the flour farinograph (Brabender OHG, Duisberg, Germany). According to AACC approved method 54–21 (AACC, 1984), 297.2 g of the flour samples were used to determine the attributes and prepare dough sample. The main attributes of the flour determined by the farinograph are 3.1 min of arrival time, 67% arrival time absorption at 500 BU (Brabender units), 14.4 min of departure time, 11.3 min of stability time, 11.2 min of peak time, and 34 BU mixing tolerance index. Water was added to the flour until the moisture content reached 67% with the total dough weight of 781 g; no other ingredient was added, and the sample was mixed at 25 °C and was kneaded at a speed of 63 ± 2 r/min for 11.2 min before being rolled and shaped.

2.2. The UAF system

An ultrasonic bath system (Song et al., 2009) was used for dough immersion freezing assisted with ultrasound with a 50% (v/v) glycol (AR, the Chemical Reagent Factory, Tianjin, China) water solution as the coolant. The ultrasonic equipment with 25 kHz frequency was fabricated to meet our specifications with tunable electric power at the range of 0–450 W, and the coefficient of electric energy converting to ultrasonic energy was approximately 90%. Piezoelectric ceramic transducers were attached to the center of the bottom of the ultrasonic tank to facilitate a uniform and steady ultrasonic irradiation throughout the dough sample.

2.3. The UAF process

In total, 750 g of dough was weighed and molded into a cylinder with 76 mm diameter and 140 mm height. The shaped dough was put into a synthetic glass cylinder with a radius of 76 mm, and the dough was tightly attached to the cylinder wall. The bottom of the dough was aligned with the cylinder bottom such that it could be tightly sealed via a Parafilm membrane. Before the UAF process, the temperature of the dough should be balanced to 25 ± 1 °C for several hours. The sealed samples were immersed in a −20 °C coolant. To avoid fluctuations of velocity in the fluid and the intensity of the ultrasound due to different positions in the ultrasound tank, all of the samples were specifically placed at the same position for each experiment. The real-time temperature at the geometric center of each sample (i.e., the sample temperature) was measured via a T-type thermocouple, which connected to Digi-Sense 12 Channel Scanning Benchtop Thermometer, 115 VAC produced by Cole-Parmer Instrument Corporation. The sample temperatures were acquired at 1 min interval and transmitted to a computer to obtain the freezing curves. In the UAF trials, the samples were irradiated by ultrasound waves with the following conditions: 25 kHz frequency, 30 s on/30 s off duty cycle, and 0, 175, 224, 288, 360, or 418 W power levels. The freezing process ended as soon as the temperature of each sample reached −18 °C. After freezing, each sample was placed into a double high-density polyethylene bag and stored at −20 ± 1 °C which was the same temperature of coolant. Each freezing experiment was repeated in triplicate.

2.4. Scanning electron microscopy

A thin-diameter freezing dough rod (15 mm diameter and 100 mm height) was prepared with UAF processing, and after one week of freeze-storage, the rod was placed in liquid nitrogen for several minutes to make it easily fractured without distortion of the shape and the distribution of ice crystals in the frozen dough as a result of thin-diameter, and then the fractured rod was freeze-dried in a freeze-dryer Model ALPHA 1-4 (Christ Co., Germany) to prepare for the scanning electron microscopy (SEM) analysis (LEO 1530 VP scanning electron microscope (LEO Co., Germany). The angular void on the fracture face of the dried rod in the SEM image reflects the size and distribution of ice crystals in the frozen dough prepared by UAF process, whereas the larger spherical voids in the SEM image were interpreted to be the gas bubbles that were formed during dough kneading (Zounis et al., 2002a, 2002b).

The fracture surface of the thin-diameter freezing dough rod was sampled, and its bottom was fixed on the stage of a LEO 1530 VP scanning electron microscope (LEO Co., Germany) with conductive, double-sided adhesive tape. Gold preprocessing was performed under vacuum conditions prior to being observed under SEM. The SEM images of the samples were digitally captured at different locations at a 100× magnification.

2.5. FTA test for frozen dough

Samples that were frozen under either ultrasonic irradiation or conventional immersion freezing were analyzed using a TA-XY2 food texture analyzer (Stable Micro Systems, U.K.). After immersion freezing and freeze storage at −20 ± 1 °C for one week, 50 g of the freezing dough was thawed under constant temperature (23 ± 2 °C) and relative humidity (60 ± 5%), and this specimen was rolled out into a 1-mm-thick frozen dough wafer on a sheeter. A 0.75-S glass, spherical FTA probe was employed to penetrate the frozen dough wafers at a fixed velocity, and the maximum penetration distance and penetration force of the frozen dough wafers were obtained based on the curve of the wafers stress as a function of time. The values that are reported herein are the average of three replicated measurements.

2.6. GC–MS analysis on frozen dough

The volatile compounds in the frozen dough were extracted and determined by solid-phase micro-extraction-gas chromatography–mass spectrometry (SPME–GC–MS). The compounds were extracted from 5 g frozen dough by SPME using a 65 μm polydimethylsiloxane-Carboxen fiber (Supelco, USA) for 1 h at 60 °C in a water bath, and then the extracted compounds were introduced directly into the injector of the GC–MS (Thermo fisher, USA) for desorption at 250 °C for 3 min in the splitless mode to be separated and analyzed with a fused silica coated column DB-