Available online at www.sciencedirect.com

ScienceDirect

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

Influence of power ultrasound on ice nucleation of radish cylinders during ultrasound-assisted immersion freezing

Baoguo Xu [a], *Min Zhang* [a,*], *Bhesh Bhandari* [b], *Xinfeng Cheng* [a]

[a] *State Key Laboratory of Food Science and Technology, Jiangnan University, 214122 Wuxi, Jiangsu, China*
[b] *School of Agriculture and Food Sciences, University of Queensland, Brisbane, QLD, Australia*

ARTICLE INFO

Article history:
Received 12 May 2014
Received in revised form
5 July 2014
Accepted 12 July 2014
Available online 22 July 2014

Keywords:
Power ultrasound
Nucleation
Immersion freezing
Radish cylinders

ABSTRACT

The effect of ultrasound-assisted immersion freezing on the dynamic nucleation of ice and the delay from ultrasound application onset to nucleation commencement of radish cylinder samples were studied. The samples were frozen in 30% (w v^{-1}) $CaCl_2$ solution (−20 °C) in an ultrasonic bath system. To evaluate nucleation, ultrasound irradiation (20 kHz) was carried out with different durations (0 s, 3 s, 7 s, 10 s or 15 s), onset temperature (−0.5, −1, −1.5 and −2 °C) and intensities (0.09, 0.17, 0.26 and 0.37 W cm^{-2}). The results showed that ultrasound irradiation was able to induce nucleation and the nucleation temperature of radish cylinder samples exhibited a good fit to linear equation with the ultrasound irradiation temperature under 7 s duration and 0.26 W cm^{-2} intensity. Ultrasound irradiation temperature at −0.5 °C for 7 s duration with intensity of 0.26 W cm^{-2}, was an optimal ultrasound application conditions for the nucleation inducement of radish cylinder samples. The results of the current study implied that ultrasound offered promising application to control the crystallization process in freezing of solid foods.

Influence des ultrasons sur la nucléation de la glace dans des cylindres de radis pendant la congélation par immersion assistée par ultrasons

Mots clés : Ultrasons ; Nucléation ; Congélation par immersion ; Cylindres de radis

1. Introduction

Radish (*Raphanus sativus* L.), belonging to the Brassicaceae family, is an important worldwide root vegetable crop, especially in East Asia, due to its wide adaptation, high yield and abundant nutritional content (Lu et al., 2008). However, fresh radish has a limited shelf-life. Freezing is a well-known preservation technique to maximize the shelf life and

* *Corresponding author*. Tel./fax: +86 510 85877225.
E-mail address: min@jiangnan.edu.cn (M. Zhang).
http://dx.doi.org/10.1016/j.ijrefrig.2014.07.009

preserve the quality of food products (Awad et al., 2012; Kiani and Sun, 2011).

It is well-known that water transformation into very small ice crystals preserves the food structure during freezing process. Crystallization is a phase transition phenomena occurring during the freezing process which progresses through two steps: the formation of nuclei (namely nucleation) and subsequent growth of the nuclei to a specific crystal size, orientation and shape (Kiani and Sun, 2011). The nucleation, which strongly influences the morphology, size and distribution of ice crystals, is considered as a critical factor for the optimization of freezing industrial processes (Nakagawa et al., 2006; Petzold and Aguilera, 2009). To initiate the nucleation, the water needs to be supercooled below the freezing temperature. Meanwhile, since the nucleation is more energetically demanding than crystal growth and has a remarkable influence on the crystallization rate, lots of new approaches have been developed to explore the nucleation behaviors of water. Among these approaches, sonocrystallization, which is the use of power ultrasound to control the crystallization process, has proved to be very useful, because it can enhance both the nucleation rate and the crystal growth rate (Delgado and Sun, 2011). However, the temperature at which nucleation takes place is uncertain due to the fact that it occurs spontaneously and stochastically, implying that nucleation possesses probabilistic nature. Therefore, a method, which can control the nucleation phenomena and change its stochastic behavior into a repeatable and predictable manner would be valuable and favorable for the food freezing industry (Kiani et al., 2011).

Ultrasound is defined as the energy generated by sound waves of frequencies above the human hearing, from 16 kHz up to the MHz range (Awad et al., 2012; Comandini et al., 2013; Mason et al., 2003; Schössler et al., 2012). Power ultrasound, in particular, a kind of ultrasound wave with frequencies in the range from 20 to 100 kHz and high sound power or sound intensity (generally higher than 1 W cm^{-2}) has been addressed as a novel technique to improve the freezing and crystallization processes (Chang et al., 2012; Delgado et al., 2009; Fernandes et al., 2008; Fonteles et al., 2012; Guan et al., 2011; Kiani et al., 2012b; Mason, 1998). Many scientists had reported that the nucleation of water can be induced by irradiation of power ultrasound waves. Chow et al. (2003, 2004; 2005) reported that ultrasound irradiation showed its ability to initiate nucleation in supercooled aqueous solutions. Saclier et al. (2010) and Ruecroft et al. (2005) reported that power ultrasound was employed to trigger nucleation in industrial crystallization processes of organic molecules. Therefore, the power ultrasound used to manipulate nucleation and improve the repeatability of the process can be a promising method.

Some literatures had focused on the mechanism of ultrasound induced nucleation of immersion freezing. Kiani et al. (2011) investigated the ultrasound assisted nucleation of some liquid and solid model foods during freezing. They indicated that the Hickling's theory was not adequate to describe the ultrasound-assisted nucleation and secondary phenomena (such as flow streams) were also important for the initiation of nucleation. Kiani et al. (2012a) also reported the effect of power ultrasound on the nucleation of water during freezing of agar gel samples in tubing vials and indicated that ultrasound irradiation was able to initiate nucleation at different supercooling temperatures in agar gel if optimum intensity and duration of ultrasound were chosen. Delgado et al. (2009) reported that different ultrasound treatments, including ultrasound exposure time and applications/intervals on apple cylinders, had some evidences on the stimulation of primary nucleation. However, due to the probabilistic occurrence of the nucleation temperature, the exact mechanism of ultrasound induced nucleation remains uncertain.

The aim of the present research is to investigate the effect of ultrasound waves on the nucleation of water in radish cylinders at different supercooling temperatures with different power intensities and irradiation durations. Studying the effect of ultrasound on the nucleation of water in radish samples can be valuable for the investigation of the nucleation mechanism in complex food systems.

2. Materials and methods

2.1. *Raw materials*

Fresh radishes (90.7% w w^{-1} moisture content, wet basis) in this study were purchased from a local supermarket. They were washed and cut into radish cylinders measuring 2.5 cm diameter and 3.0 cm high using a regular steel mold. The radish cylinders were kept in a refrigerator at a temperature of 4 °C to achieve uniform initial temperature until measurements were taken and used up within 2 days. Moisture lost, water or solute uptake during this period was considered to have little effect.

2.2. *Experimental apparatus*

A laboratory scale experimental set up for this research was developed in Ningbo Scientz Biotechnology Co., Ltd., China,

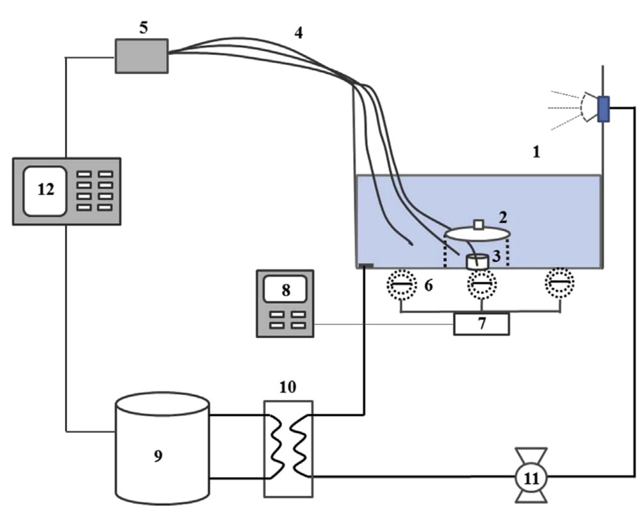

Fig. 1 – Schematic diagram of the freezing equipment. (1. Immersion freezing tank 2. Sample cage 3. Sample 4. Type K thermocouples 5. Temperature controller 6. Ultrasound transducers 7. Ultrasound generator 8. Control system of ultrasound 9. Refrigeration units 10. Refrigeration cycle system 11. Pump 12. Control panel).