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Effect of freezing under electrostatic field on selected properties of an agar gel

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ABSTRACT

The objective of this study was to investigate the effects of electrostatic freezing on the quality attributes of freeze-thaw agar gel. Agar gels were frozen under static electric field 0–5.8 × 10^4 V m^{-1} at − 20 °C. Freezing rate and energy consumption were monitored during the freezing process and microstructures of the formed ice crystals were also analyzed by light microscopy techniques. Agar gel quality changes (syneresis and texture) were evaluated after thawing the frozen samples at + 4 °C. Results showed that the energy used by a DC high voltage generator was negligibly small as compared to the energy consumption by a freezer, and the freezing rate was not significantly influenced by electrostatic freezing (ESF). ESF also reduced the size of ice crystals but did not cause obvious changes in syneresis and texture of the samples.

Industrial relevance: The effects of electrostatic field freezing on the quality attributes of agar gel have been investigated. The results showed that the electrostatic freezing can be used as a potential tool to improve the microstructure of foodstuffs during freezing.

1. Introduction

Preservation of a food product by holding at some temperature below its freezing point is a very well known process, but ice crystals formed during this process would cause damage to food quality including appearance, sensory properties, textural attributes and nutritional value (Delgado & Sun, 2001; Fellows, 2009). Therefore, considerable effort has been taken to reduce the damage induced by freezing in biological tissues, with a focus on reduction of the size of ice crystals. This aim can be achieved by altering the freezing method, for instance cryogenic freezing or by application of novel freezing techniques, such as radiofrequency assisted freezing (Anese et al., 2012), microwave assisted freezing (Xanthakis, Le-Bail, & Ramaswamy, 2014), resonant or oscillating magnetic field (Fikiin, 2008) and static magnetic field freezing (Lin et al., 2015).

Electrostatic freezing (ESF) systems involve the application of high voltage DC power supply to food during freezing. Most research in this area has been focused on the ESF effect on ice nucleation in aqueous solutions. Orlowska, Havet, and Le-Bail (2009) showed that utilization of high electrostatic fields is a reliable method of controlling ice nucleus formation in water (Orlowska et al., 2009). The effect of static electric field on the microstructure of the solid food has been reported recently by Xanthakis, Havet, Chevallier, Abadie, and Le-Bail (2013). Their results showed that the average equivalent circular diameter, decreased with increasing strength of the static electric field. Today, ESF systems are considered superior and novel technique due to the reduction of damage to food microstructure during freezing and improving the quality of frozen products.

This technology may also have some drawbacks and safety issues including, high voltage operation in a humid environment, partial discharges and sparking. The main limitation of this technology is that the maximum thickness of food materials must be smaller than the distance between two electrodes (Dalvi-Isfahan, Hamdami, Xanthakis, & Le-Bail, 2017; Le-Bail, Orlowska, Havet, Adedeji, et al., 2011b; Muthukumaran, Orsat, Bajgai, & Raghavan, 2009). The precise mechanisms of ESF are not well understood; however, it is generally accepted that ESF can affect the molecular dynamics of water by polarizing their dipoles and aligning them to the direction of electric field. Therefore, the energy barrier (activation energy) to nucleation can be reduced and the nucleation rate could be increased (Dalvi-Isfahan, Hamdami, & Le-Bail, A., 2016b; Le-Bail, Orlowska, & Havet, 2011; Vegiri, 2004a, 2004b). Furthermore, ESF tends to induce ice nucleation at a lower degree of supercooling, and subsequently shorter nucleation times and longer solidification times will result. The modification of

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solidification time may be caused by the amount of refrigeration energy stored during the supercooling. Since ESF decreases nucleation time, more heat must be removed during phase transition, which results in longer solidification times (Orlowska, Le-Bail, & Havet, 2014; Wei, Xiaobin, Hong, & Chuanxiang, 2008). Despite the noticeable impact of ESF on the nucleation in an aqueous solution has been established in the literature, further research is needed to better understand and optimize the technology before its industrial and commercial application.

Agar gel is a high water content model food. It is very sensitive to freezing and has been considered for this study to investigate the effect of ESF on selected quality and physical parameters of agar gel.

2. Material and methods

2.1. Materials

Agar gel was chosen because it is considered to be an isotropic and homogenous material, and it can be easily reproduced in any kind of geometry (Chevalier, Le-Bail, & Ghoul, 2000). Agar powder (Biolife Italia, Italy) was mixed with sucrose (Merck, Germany) and distilled water in the ratio of 2:8:90. The agar solution was heated until the agar powder was totally dissolved. This was confirmed in obtaining a uniform and clear liquid. Then, the mixture was poured into a mold and stored at 5 °C for 24 h to achieve stabilization. The gel samples were then cut into cylinders (20 mm diameter × 10 mm height). The samples were covered with a polyethylene film to avoid moisture evaporation before experimentation.

2.2. Experimental set-up

The specification of the sample holder has been described in detail previously (Dalvi-Isfahan et al., 2016a). In brief, the experimental set-up was comprised of a DC voltage generator with output voltage up to 50 kV (LS50KV-5 mA, China), one pair of rectangular copper plate electrodes with the dimensions of 50 × 50 and 65 × 65 mm placed in parallel as upper and lower electrodes, respectively, and sample holder.

The polyethylene sample holder with dimensions (80 × 80 × 18 mm) was constructed and the agar sample was placed in a cylindrical cell located in the center of sample holder (measurement cell) (Fig. 1). The sample holder was pre-cooled to 5 °C in a cold incubator for one hour before the start of the measurement. Temperature changes in the center of the sample were recorded by the real-time measurement system consisting of a fiber optic thermometer system (FOB100 Series, 4-channel, accuracy ± 0.8 °C, OMEGA Engineering, Inc., Canada) connected to a fiber optic sensor. During measurements, temperature changes of the sample were recorded using FOB100 software and data stored in a PC *via* the RS232 communications port once second. The experiments were conducted in an air blast freezer at − 20 °C and the temperature inside the freezing tunnel remained nearly constant with the tolerance of ± 0.5 °C. Since an applied voltage level higher than 12 kV can cause changes in the current flowing through the circuit, the applied voltages for the experimental groups were set at 0, 4, 8 and 12 kV. After freezing, the samples were weighed and covered with a polyethylene film to avoid moisture evaporation, and moved to a cold incubator (Wisecube, WIG-105, Korea) at 4 °C for 2 h, then analyzed for syneresis and texture.

2.3. Electric field strength

Since in our system the electric field is non-uniform, the electric field intensity could not be obtained simply by dividing the applied voltage potential by the distance between the two electrodes. Therefore, a pure electrostatic problem has to be solved to determine the electric field intensity applied to the agar gel sample. Modelling was done by solving Laplace equation using COMSOL Multiphysic® software. The dielectric permittivities ε_r of the materials were 1, 2.5 and 80 respectively for the air, the container and the sample (Agar).

The electrostatic potential, V, is governed by Laplace's equation.

$$\nabla^2 V_i = 0 \tag{1}$$

The boundary conditions can be described as follows:

The top electrode ($z = h / 2$) is maintained at a constant voltage V_0; the bottom electrode ($z = - h / 2$) is grounded: At the other external boundaries, it is assumed that the field is directed only in the z-direction.

$$\begin{aligned} &V(z = h/2) = V_0 \\ &V(z = -h/2) = 0 \\ &(\nabla V)\cdot n = 0 \quad \text{at } (y = \pm L/2) \end{aligned} \tag{2}$$

At the interfaces between the dielectric regions, the potential satisfies the following conditions:

$$\begin{aligned} &V_i = V_j \\ &(\varepsilon_i \nabla V_i - \varepsilon_j \nabla V_j)\cdot n = 0 \end{aligned} \tag{3}$$

where ε_i is the dielectric constant of region i, and n is the unit normal vector directed from region i to region j. Finally, after solving for the electric potential throughout the domain, we compute the average electric field in the centre of measurement cell (Stan, Tang, Bishop, & Whitesides, 2010).

$$E = \int - \nabla V dv \tag{4}$$

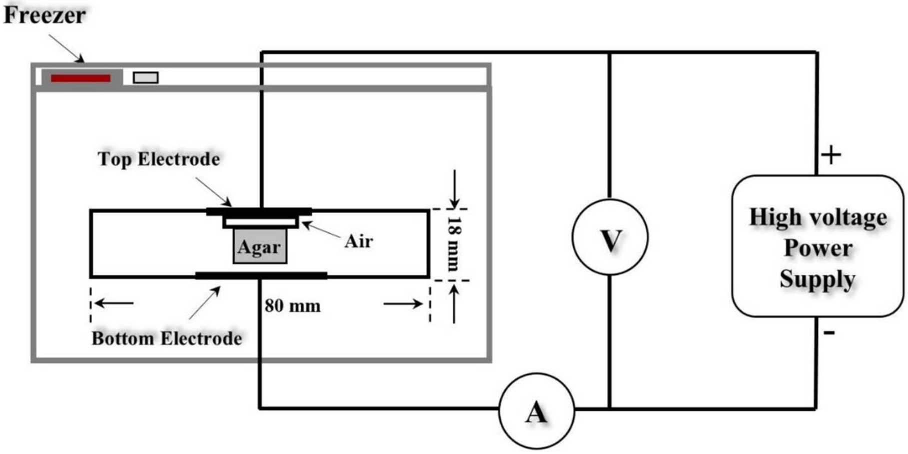

Fig. 1. Schematic diagram of the experimental set-up.