Journal of Food Engineering 120 (2014) 31–36

Contents lists available at ScienceDirect

Journal of Food Engineering

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

Magnetic separation technique on binary mixtures of sorbitol and sucrose

Syou Maki [a,*], Noriyuki Hirota [b,1]

[a] Laboratory of Molecular Chemistry, Faculty of Pharmacy, Osaka Ohtani University, 3-11-1, Nishikiori-kita, Tondabayashi City, Osaka Pref. 584-8540, Japan
[b] Materials Processing Unit, National Institute for Materials Science, 1-2-1 Sengen, Tsukuba, Ibaraki Pref. 305-0047, Japan

ARTICLE INFO

Article history:
Received 18 February 2013
Received in revised form 9 July 2013
Accepted 10 July 2013
Available online 20 July 2013

Keywords:
Food processing
Superconducting magnet
Magneto-Archimedes levitation
Magnetic force

ABSTRACT

We separated binary mixtures of sucrose (disaccharide) and sorbitol (monosaccharide) by the effect of magneto-Archimedes levitation as a first step in proposing a new separation technique in food processing. In this technique, the mixtures are levitated at a specific position in a superconducting magnet, and the separation is realized by controlling the magnitude of magnetic force. Owing to the differences in their magnetic susceptibility, the levitating position of the components in the mixtures is uniquely identifiable. The aggregates of sorbitol were levitated upwards and those of sucrose were levitated downward. As the magnitude of the magnetic force was reduced, the sucrose and then the sorbitol fell in that order, and therefore they could be collected separately. The mechanism of this effect is attributed to the 8.2% difference in the volumetric magnetic susceptibilities of sucrose and sorbitol and the compressed oxygen gas. In the separation process, the falling particulates were distributed in an hourglass shape. This phenomenon was induced by the horizontal component of the magnetic force. The curvilinear surface was in good agreement with a numerical simulation.

1. Introduction

Magneto-science and magneto technology have promising potential in many kinds of industries. For example, various applications of magnetic forces have been reported in protein crystallization (Astier et al., 1998; Ataka and Wakayama, 2002; Lin et al., 2000; Maki et al., 2004, 2009; Yin et al., 2003), in the field of chemistry (Chie et al., 2003; Kimura, 2003; Kitazawa et al., 2001; Tagami et al., 1999; Tanimoto et al., 2005), in medical innovation (Nishijima et al., 2008), and in the environmental arena (Sakaguchi et al., 2009; Fang et al., 2010). However, few techniques using a magnetic force have yet been used in food engineering, primarily because there are very few reports about the possible biological influences of magnetic forces, i.e. denaturation and toxicity. Safety advantages, in particular, would be indispensable in food engineering.

In general, it is difficult to separate different types of edible particles without denaturing them in the process. *Magnetic separation* utilizes the magnetic susceptibility of the particles to separate them, so that a mixed matter can be quickly separated without a chemical reaction. We believe that magnetic separation would be the most highly qualified technique to perform such separations.

Furthermore, non-destructive and non-contact separation can be realized with magnetic levitation. Magnetic levitation is free from any contamination from equipment, so it is the most hygienic of the innovative separation techniques using a magnetic force. In addition, this technique is suited for separating diamagnetic substances (e.g., organic matter). It is noteworthy that magnetic levitation is applicable to most food products.

Some research (other than in food engineering) about using magnetic levitation to separate mixtures has already been reported (Catherall et al., 2003; Fujiwara et al., 2001; Hirota et al., 2002, 2004; Ikezoe et al., 2000; Kimura et al., 2000; López-Alcaraz et al., 2007; Maki and Ataka, 2007; Hayashi et al., 2010). However, the separated substances in those studies were relatively large matters. Soluble fine particulates were rarely discussed, except in Kitazawa's report (2001).

In our experiment, we separated sorbitol from sucrose by magnetic levitation. Sucrose is a disaccharide derived from glucose and fructose, and is commonly known as table sugar. On the other hand, sorbitol is a monosaccharide, and is used as a sugar substitute. As is known, it is difficult to distinguish sorbitol from sucrose by appearance.

In this paper, we will present the effects of magnetic force on levitating fine particles by means of *in situ* observation and numerical computations. Because of the water solubility of sugar, we performed *magneto-Archimedes levitation* in compressed oxygen gas. Magneto-Archimedes levitation (Ikezoe et al., 1998), the principle of which is presented in the next section, is a useful technique for separating diamagnetic substances in a small magnetic field.

* Corresponding author. Tel.: +81 721 24 9468; fax: +81 721 24 9890.
E-mail addresses: makisyo@osaka-ohtani.ac.jp (S. Maki), HIROTA.Noriyuki@nims.go.jp (N. Hirota).
[1] Tel.: +81 29 863 5619.

0260-8774/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jfoodeng.2013.07.006

2. Theoretical considerations

For the purpose of exploring the possibility of magneto-Archimedes levitation as an analyzer, we focused on the quantitative relationship between the experimental results and numerical computations. Therefore, we will present the theoretical equation of magnetic separation in this section. Magnetic force $\boldsymbol{F}$ (f_x,f_y,f_z) N/m^3 is presented as follows (Faraday, 1847):

$$\boldsymbol{F} = \frac{\chi_v}{2\mu_0}\mathrm{grad}(\boldsymbol{B}^2) \quad (1)$$

where χ_v is the volumetric magnetic susceptibility (dimensionless), denoted by the product of the density ρ kg/m^3, and the mass magnetic susceptibility χ_m m^3/kg. Magnetic susceptibility indicates the degree of magnetization of a material in response to an applied magnetic field. Note that magnetic susceptibility is substance-specific. μ_0 is the permeability of vacuum H/m. $\boldsymbol{B}$ (b_x,b_y,b_z) is the magnetic flux density T. We defined the center of the magnet as $z = 0$, and the plus sign means upward (see the schematic illustration in Fig. 1). This equation indicates that the magnetic force becomes greater as grad($\boldsymbol{B}^2$) becomes larger. In a superconducting magnet, two maximum points of grad($\boldsymbol{B}^2$) exist near the edge of the coil. Note that grad($\boldsymbol{B}^2$) becomes almost zero around the coil center, whereas $\boldsymbol{B}$ reaches its maximum in the bore because a magnetic field directs uniformly there. The distribution of grad($\boldsymbol{B}^2$) is plane symmetric with respect to the coil center, and it directs downward over the coil center.

Magnetic levitation is realized with f_z, which is the vertical component (z-component) of the magnetic force. Levitating force f_z (N/m^3, upward positive) by the vertical magneto-Archimedes effect is approximated by the following equation.

$$f_z = \frac{(\chi_{v1} - \chi_{v2})}{\mu_0}B_z\frac{d}{dz}B_z \quad (2)$$

In this method, the magnetic susceptibilities of the substance (subscript 1) and the medium surrounding the substance (subscript 2) are intentionally reversed. In order to levitate the diamagnetic substance, it should be in a paramagnetic substance, and set up over the coil. That is, $\chi_{v1} - \chi_{v2}$ is negatively increased by the superposition of the magnetic susceptibilities. On the other hand, the sign of $B_z\mathrm{d}B_z/\mathrm{d}z$ is negative over the coil. Hence, f_z is effectively enhanced.

We used compressed oxygen to levitate the diamagnetic substance ($\rho_m\chi_m < 0$). The use of compressed oxygen gas is the first step to present the viability of the magnetic separation technique in food processing. This method is expressed as follows:

$$f_z = \frac{(\rho_m\chi_m - \rho_{\mathrm{oxygen}}\chi_{\mathrm{oxygen}})}{\mu}B_z\frac{d}{dz}B_z + (\rho_m - \rho_{\mathrm{oxygen}})g \quad (3)$$

where ρ_{oxygen}, χ_{oxygen} and g are the density of oxygen (kg/m^3), mass magnetic susceptibility of oxygen (m^3/kg), and gravitational acceleration (m/s^2), respectively. ρ_m and χ_m are the density (kg/m^3) and mass magnetic susceptibility (m^3/kg) of the object, respectively. The coefficient of $B_z\mathrm{d}B_z/\mathrm{d}z$ is enhanced dramatically by the assistance of a large magnitude of χ_{oxygen}. Furthermore, the effect becomes tangible owing to the compression of ρ_{oxygen}. In addition, the buoyancy force (the second term), no matter how little, helps to levitate the diamagnetic substance. For these reasons, separation can be realized with a small magnetic field. When the substance being levitated is in a stable condition, the force balance becomes zero. Thus, the levitating position reflects on the magnetic susceptibilities of the substances.

3. Materials and methods

3.1. Materials

We used commercial sucrose and sorbitol, in which no adjustments were made to the ingredients at all. By means of a superconducting quantum interference device (MPMS-5S, Quantum Design Co., Ltd), the mass magnetic susceptibilities of sucrose and sorbitol were found to be $-(5.06 \pm 0.02) \times 10^{-9}$ and

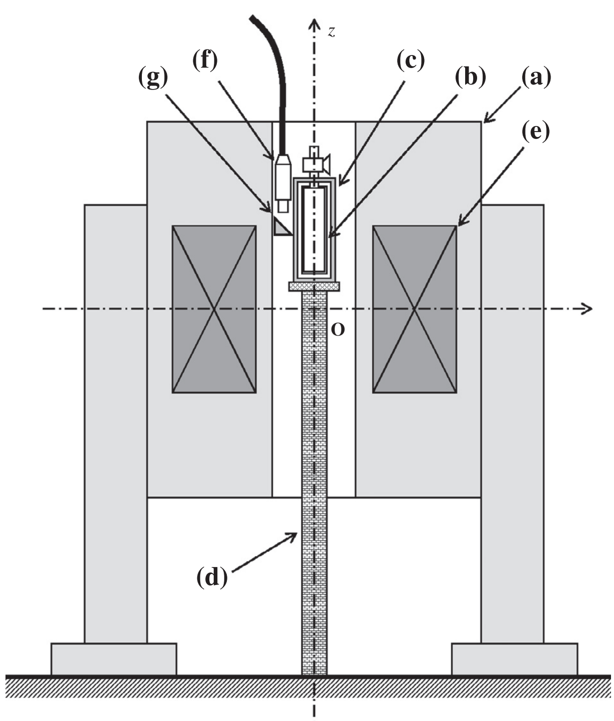

Fig. 1. Schematic illustration of the experimental equipment: (a) a superconducting magnet, (b) a sample vessel to separate sucrose from sorbitol. The inside diameter and the height were 27 and 217 mm, respectively. This vessel was also filled with compressed oxygen gas in order to enhance the magnetic levitation, (c) a cylindrical tempered polycarbonate protector, (d) a vessel stand, (e) a superconducting magnet coil. The separation was carried out at the upper edge of the magnet coil, (f) a CCD camera and (g) a prism.

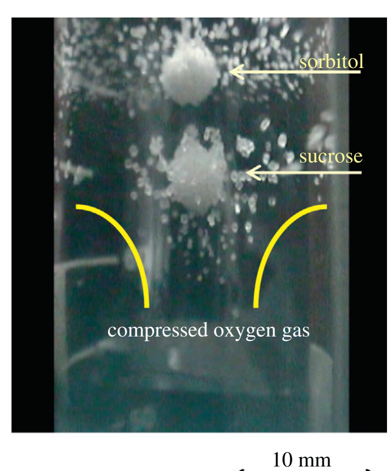

Fig. 2. Typical image of the magnetically separated sucrose and sorbitol in compressed oxygen gas. The upper levitating condensation is sorbitol ($z = 158$ mm), and the lower one is sucrose ($z = 152$ mm). The distribution of the small particles reminds us of an "hourglass-shaped" figure. A visual guide to present this figure was added to this image (yellow solid curves). Magnetic induction at $z = 0$ was 12.70 T. The pressure of compressed oxygen gas was 1.58 MPa.