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Analysis of electrostatic powder charging for fractionation of foods

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ABSTRACT

Electrostatic separation based on different tribo-electric charging behaviours of components has emerged as a novel, sustainable dry fractionation process. This study aims to characterise charging behaviour of single-component particles in nitrogen gas flowing through aluminium tubes. Experiments were carried out with polystyrene (PS) particles and wheat gluten as model particles. Results indicated that specific charge increased linearly with gas velocity up to 28 m/s for both materials. It was found that surface charge densities of different-sized PS particles overlapped for laminar gas flow, whereas for higher stronger gas flow rates, surface charge density of the smallest particles deviated from that of larger particles. Specific charge of PS particles increased linearly with increasing tube length from 125 to 225 mm. Additionally, charging of PS particles was unaffected by relative humidity (RH) of gas; however, specific charge of wheat gluten decreased for RH > 80%. Concluding, these results provide insight in critical parameters affecting charging behaviour, thus facilitating the development of electrostatic separation processes to fractionate food ingredients.

Industrial relevance: Conventional wet fractionation of food ingredients uses copious amounts of water and energy, and causes loss in native functionality due to the harsh conditions such as high temperature and pH. Dry fractionation by milling and dry separation offers a more sustainable and mild fractionation route. Electrostatic separation, being a novel dry separation process, has the potential to be used in food ingredient production, especially when particles differ little in density and/or particle size. The charging step is critical to the effectiveness of the separation. Hitherto, charging behaviour of agro-materials has not been well characterised, especially at high gas velocities. This study provides input for developing electrostatic separation processes for fractionation of food ingredients.

1. Introduction

Conventional wet fractionation of agro-materials into food ingredients uses copious amounts of water and energy. Moreover, the harsh conditions during wet fractionation, such as high temperature and pH, are detrimental to the native functionality of individual components. In contrast, dry fractionation is a more sustainable alternative and retains the functionality of the produced fractions significantly better (Schutyser & van der Goot, 2011). Dry fractionation conventionally, e.g. for pea fractionation, combines milling and air classification or sieving to obtain protein and starch enriched fractions (Pelgrom, Schutyser, & Boom, 2013; Pelgrom, Vissers, Boom, & Schutyser, 2013). Milling is applied to achieve the physical disentanglement of individual components while air classification or sieving fractionates the millings on the basis of particle density and/or particle size into enriched fractions. However, especially when particles differ little in density and/or particle size, the final purity that can be achieved towards a specific component is limited.

More recently, electrostatic separation has emerged as a novel process for dry food ingredient fractionation, although the principle has been applied for decades for mineral enrichment (Fraas & Balston, 1940; Gaudin & Mora, 1958; Kwetkus, 1998; Trigwell, Tennal, Mazumder, & Lindquist, 2003). The separation is based on differences in tribo-electric charging behaviour of materials (Higashiyama & Asano, 1998; Kelly & Spottiswood, 1989b). It is achieved by charging particles with a gas-assisted flow in a charging device. The subsequent particle separation takes place under the influence of an external electrostatic field (Fraas & Balston, 1940; Kelly & Spottiswood, 1989c).

The charging step is critical to the effectiveness of the separation and is based on the phenomenon that two different materials become charged when they rub against each other. When two surfaces contact with each other, depending on the surface states, electrons will transfer from one surface to the other. Upon separation, the two surfaces become charged in the same amount but with opposite polarities (Bailey, 1984, 1993; Kelly & Spottiswood, 1989a; Matsusaka, Maruyama, Matsuyama, & Ghadiri, 2010). Tribo-electric charging is influenced by many factors, such as the chemical, physical and electrical properties of particle and contact surface (Bailey & Smedley, 1991; Carter, Cassidy, Rowley, & Merrifield, 1998; Eilbeck, Rowley, Carter, & Fletcher, 1999; Gajewski, 1989; Rowley, 2001), number of impacts (Matsusaka, Ghadiri, & Masuda, 2000; Matsuyama & Yamamoto, 1995), and velocity and angle of the impact (Matsuyama & Yamamoto, 1994; Yamamoto & Scarlett, 1986). Moreover, environmental conditions such as temperature and

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relative humidity also affect the charging (Bailey & Smedley, 1991; Gajewski, 1989; Nguyen & Nieh, 1989; Nomura, Satoh, & Masuda, 2003; Rowley & Mackin, 2003). While several studies have demonstrated the possibility of using electrostatic separation to fractionate agro-materials, e.g. for the production of aleurone-rich fractions from (fine) milled wheat bran (Bohm, Bogoni, Behrens, & Otto, 2003; Hemery et al., 2009; Hemery et al., 2011), the tribo-electric charging behaviour of agro-materials has not yet been systematically studied.

The aim of the study reported here is to characterise tribo-electric charging behaviour of single-component particles under different conditions. Purified wheat gluten was used as an agro-material. Moreover, well-defined spherical particles made from polystyrene were used as a model system to avoid the complexity caused by the natural composition and irregular shape of agro-materials. Three aluminium tubes with different lengths were used to charge particles. The experiments were designed to evaluate the influence of several factors: the carrier gas velocity, the particle size, the charging tube length, the carrier gas relative humidity and the material water activity.

2. Materials and methods

2.1. Materials

Three differently sized Spherical Polystyrene® (PS) particles were purchased from Maxi-Blast, Inc. (US). The particle size distributions were measured by Mastersizer 2000 with the Scirocco 2000 dry dispersion unit (Malvern Instruments, Worcestershire, UK). The volumetric mean diameters, D[4,3], were 218 μm, 304 μm and 450 μm, respectively. A scanning electron microscope (SEM) image of PS particles was made by Phenom G2 pure Scanning Electron Microscope (Phenom-World BV, The Netherlands). Fig. 1-A shows that the PS particles were perfectly spherical and had a smooth surface.

Vital wheat gluten was obtained from Roquette (France) with the following specifications: moisture 6% (w/w), protein 75–80% (w/w), starch 9% (w/w), cellulose <1% (w/w), fat 7% (w/w) and ash 1% (w/w). A SEM image is shown in Fig. 1-B and it can be observed that the particles have an irregular shape and a rough surface with pores smaller than several microns.

2.2. Charging experiments

A lab-scale electrostatic charging device consisting of a funnel and a squared charging tube, both made from aluminium, was used for charging experiments (Fig. 2). The inner dimension of the tube was 1.8 mm × 1.8 mm. To avoid any external electrical interference the charging tube was shielded by wrapping the tube with an insulating plastic foil and then an aluminium foil layer which was grounded. The funnel was also grounded via direct contact with the aluminium foil layer. An electrometer (Keithley Model 6215) was connected to the charging tube to measure the impact charge obtained by the tube. Since the particles and the tube are charged in the same amount but opposite polarities, the read charge Q_{read} needs to be converted into the charge of particles Q_p by Eq. (1).

$$Q_p = -Q_{read} \tag{1}$$

Two terms were used to express the charge obtained by the particles: the specific charge which is defined as the charge-to-mass ratio (in μC/g) and the surface charge density, which is defined as the charge-to-surface ratio (in $\mu C/m^2$).

Before each charging experiment, the entire system was flushed with nitrogen. Then the electrometer was corrected for zero reading and 3 g of sample was poured into the funnel. According to Bernoulli's law, a pressure drop exists between the funnel and the nitrogen gas flowing through the tube at the outlet of the funnel. This phenomenon is also known as the Venturi effect. The pressure difference (Δp) is proportional to the kinetic energy of the flowing gas in the tube as expressed with Eq. (2).

$$\Delta p = \frac{1}{2}\rho_g v_g^2 \tag{2}$$

where ρ_g is the density of the nitrogen, and v_g is the velocity of the nitrogen gas. Due to this pressure difference, particles are drawn into the charging tube. Subsequently, particles are accelerated by the nitrogen flow in the tube, and impact and exchange charge with the tube wall. The cumulative charge on the tube was measured by the electrometer. After the complete sample was dispersed in the tube, the final reading of the electrometer was recorded. Thereafter, the funnel and charging tube were cleaned with a vacuum cleaner and compressed air for the next measurement. All measurements were carried out in duplicate.

Three process parameters were varied: Gas velocity (13–36 m/s); charging tube length (125 mm–425 mm) and RH of nitrogen (0–100%). To investigate the influence of the individual parameters, only one parameter was varied at a time while the others were kept constant.

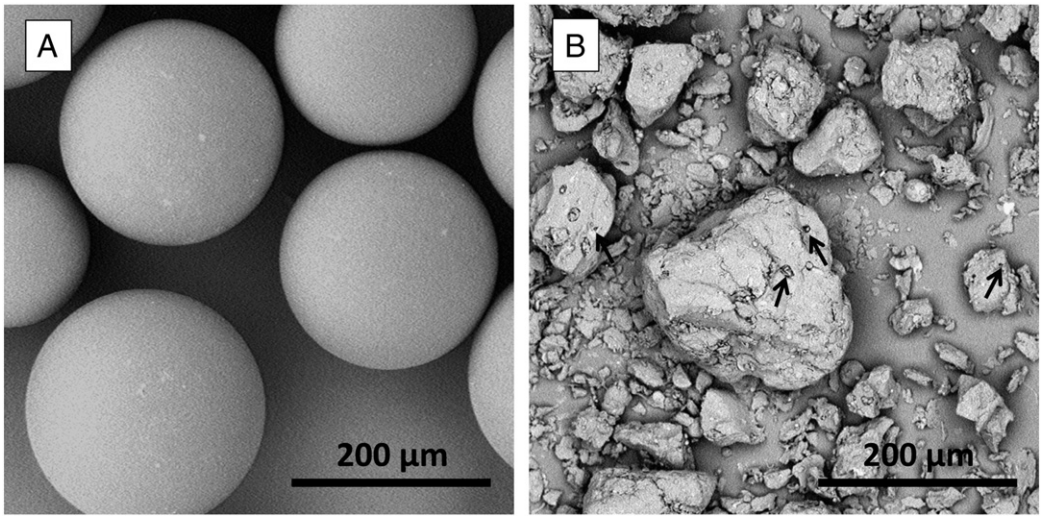

Fig. 1. Scanning electron microscope (SEM) images of A) PS particles (D[4,3] = 218 μm) and B) wheat gluten (D[4,3] = 68.6 μm); arrows indicate the pores on the surface of wheat gluten.