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Pneumatic separation of hulls and meats from cracked soybeans

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ABSTRACT

The dehulling process of cracked soybeans was experimentally investigated in this work. The mean Sauter diameter ($d_{v,s}$) of *as-received* material was 2.70 mm, with an average proportion of 95% meats and 5% hulls for a moisture content of 11.8%. The true densities of hulls and meats were 1090 and 1267 kg/m^3, with $d_{v,s}$ of 2.11 and 2.74 mm, respectively. Hulls were mostly elutriated around 2.7–4.5 m/s and meats around 9.1–13.7 m/s. The overlap of terminal velocity profiles required a combination of pneumatic and sieving operations for optimized separation. The influence of particle concentration on continuous dehulling was investigated for three solid-to-air ratios (W/Q). The procedure that maximized particle separation was a sequence of pneumatic dehulling with $v_s = 7.4$–9.1 m/s and W/Q = 1.05 kg$_{solids}$/m^3$_{air}$, followed by screening of lifted material with sieve ASTM no. 6 and a final pneumatic separation of small hulls and meats at $v_s = 3.9 - 4.1$ m/s. An industrial scale pneumatic dehuller was built and tested for W = 6973 kg/h, $v_s = 7.6$–8.2 m/s and W/Q = 0.97 kg$_{solids}$/m^3$_{air}$. The efficiency of the pneumatic device to remove hulls from the cracked soybean was very high, with the recovery of meats with purity around 99%.

Keywords: Soybean; Hulls; Pneumatic dehulling; Terminal velocity; Elutriation

1. Introduction

Soybean is the agricultural crop with the largest planted area in Brazil. The country was the second-largest world producer and exporter of this oilseed crop in 2007, just behind the United States. The expectation for the next years is still optimistic, especially because of the increasing demand of oil sources for the food industry and recently for the biodiesel production. This fact has motivated Brazilian industries to search for cost-reducing technologies to improve the market competitiveness of soybean byproducts, especially the meal fraction, a rich protein–carbohydrate–fiber ingredient for livestock and food production.

Whole soybeans have a typical size of 5–8 mm (Duarte et al., 2004; Kocabiyik et al., 2004) and, on a dry weight basis, contain about 40% proteins, 20% lipids (oil), 35% carbohydrate and about 5% ash. The grain comprises approximately 92% kernel or meat (90% cotyledons and 2% germ) and 8% seed coat or hull (Erickson, 1995; Liu, 1997; Francis, 1999). Cleaned hulls typically have thickness of 0.4–0.5 mm (Raji and Famurewa, 2005) and contain 9.4% crude protein and 86% complex carbohydrates, a composition that makes hulls an important source of dietary fiber (Erickson, 1995). The insoluble carbohydrate fraction of hull cell walls consists of 30% pectin, 50% hemicellulose, and 20% cellulose (Gnanasambandam and Proctor, 1999; Mullin and Xu, 2001). A unique aspect of soybean hulls is that the fiber content is low in lignin and is highly digestible; therefore hulls are recognized as an excellent source of readily available energy in forage-based diets (Löest et al., 2001).

Soybean hulls are poor in oil content and are fairly abrasive. Thus it is convenient to remove them from the meat prior to the oil extraction to avoid reduction in the oil yield and wear of flaking machines (Erickson, 1995).

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Nomenclature

Ar	Archimedes number
C_D	Drag coefficient
c_m	mass concentration of particles in the air stream (kg/m^3)
c_v	volumetric concentration of particles in the air stream (m^3/m^3)
D	column diameter (m)
d_{50}	cut diameter of the cyclone collector (μm)
d_i	opening of the sieve *i* (mm)
d_P	particle diameter (mm)
$d_{v,s}$	average Sauter mass diameter (mm)
g	acceleration of gravity (m/s^2)
m	number of sieve fractions in Eq. (1)
n	exponent in Eq. (5)
P	absolute ambient pressure (Pa)
Q	volumetric air-flow rate (m^3/h)
T	temperature of the air-flow (°C)
v_s	superficial air velocity (m/s)
v_t	terminal velocity of a single representative particle (m/s)
$v_{t,susp}$	mean terminal velocity of particles in a suspension (m/s)
w_i	mass fraction of particles retained in sieve i (kg/kg)
W	mass flow rate of solids or Solids feeding rate (kg/h)
W/Q	feed ratio or Solid-to-air ratio (kg$_{solids}$/m^3$_{air}$)

Greek letters

μ	fluid viscosity (Pa s)
ρ_f	fluid density (kg/m^3)
ρ_p	true particle density (kg/m^3)

In handling and processing of several agricultural products, air is commonly used as a carrier for transport (Kılıçkan and Güner, 2006) or for separating the desirable products from unwanted materials (Gorial and O'Callaghan, 1990; Khoshtaghaza and Mehdizadeh, 2006). Therefore, the knowledge of terminal velocities of grain and impurity particles becomes essential for design and operation of pneumatic devices.

Several equations for prediction of terminal velocities are available in the literature (Hawk et al., 1966; Kunii and Levenspiel, 1997; Fayed and Otten, 1997; El-Sayed et al., 2001) but their reliability for non-spherical particles is still a controversial issue. For this reason, many researchers have measured the terminal velocities for various agricultural crops and empirically related them to other physical features such as size distribution, sphericity, porosity, moisture content, true density and bulk density (Dursun and Dursun, 2005; Polat et al., 2006; Cosçkun et al., 2006; Gupta et al., 2007; Güner, 2007; Afonso Júnior et al., 2007; Zewdu, 2007).

Likewise, aerodynamic properties are important to design equipments for cleaning, drying, processing and storing soybean products (Soponronnarit et al., 2001; Polat et al., 2006). Duarte et al. (2004) found that whole soybean with moisture content of 10.90% (w.b.), equivalent sphere diameter of 6.6 mm, true density of 1170 kg/m^3 and sphericity of 0.897, have (has?) terminal velocity of approximately 14 m/s. Similar investigations were carried out by Deshpande et al., 1993 and Polat et al. (2006). These latter authors found that for whole soybean with geometric mean diameter of 5.62 mm and 6.7% moisture content, the values for sphericity, porosity, true density and terminal velocity were respectively 0.75, 0.51, 1062.6 kg/m^3 and 7.13 m/s. For 15.3% moisture content, these values changed respectively to 0.72, 0.442, 1086.4 kg/m^3 and 9.24 m/s.

The systems used to remove hulls in industrial soybean plants today vary considerably in design and capacity. However, they all share the same principle when the basic operation is examined: the difference in terminal velocities of hulls and meats caused by their very different morphologies: the hulls being flatter, the meats more rounded. If the equipment is properly sized so that the air velocity is below the terminal velocity of the meats but above that of the hulls, then, theoretically, only hulls are aspirated and a good separation is achieved.

There are a number of air separators available, and usually the more simple and non-adjustable are the most suitable in terms of capacity and maintenance (Boling, 1979). One of the simplest pneumatic hull separators is a vertical cylindrical column in which previously cracked soybeans are fed downwardly through a rising stream of air. The lighter particles, comprised of hulls and fines, are aspirated out of the top of the column while the heavier meats continue to cascade downward. The aspirated hulls are collected in a cyclone, passed to a toaster to destroy urease activity, ground to the desired particle size and either pelleted or sold as bulk (Erickson, 1995; Wrigley, 2004).

Typical industrial recommendation is that soybeans should be cracked into a few pieces only, in order to facilitate the release of hulls from meats but also to prevent the generation of fines. In practice, however, size distribution may be broad, since the fineness of the material depends on features of the particles, such as moisture content and temperature, and of the cracking machine, such as the rollers spacing and rotating speed. A typical problem found in industry is the fact that as hull and meat particles are progressively cracked in smaller sizes, their terminal velocities become closer, precluding efficient separation (Boling, 1979). The general rule is that the generation of coarser crushed material enables easier hull aspiration without taking away too much oil stock with the fines. If a broad particle size distribution is generated in the cracking mill, then mechanical separation by sieving is advised ahead of air sifting to remove fines. So, dehulling systems based on sequences of sieving and aspiration steps are still common in the industry.

Unfortunately, much of the aerodynamic data required to optimize the dehuller operation has been gathered by trial and error methods in the soybean industry, especially because optimum separation is ultimately related to the size distributions of hull and meat particles, which in turn may vary in each industry according to the crushing operation or other physical and mechanical features of the grains. Data concerning the ranges of terminal velocities of soybean fractions are still scarce in the literature. Boling (1979) presented a very good qualitative discussion about principles of soybean dehulling and strategies of efficient hull removal by combination of screening and aspiration, but no useful data was reported. Physical properties of soybean meal, including particle size and particle size distributions, bulk density and true density, and repose angle and drain angle, were studied in the laboratory by Wang et al. (1995), but no terminal velocity data was reported.