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Granular bond number model to predict the flow of fine flour powders using particle properties

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ABSTRACT

In order to improve the fundamental understanding of fine flour flow behavior, which is essential for the success of sieving and other particulate size based separation processes, this study investigates the relationship between particle properties and the flow function coefficient, a metric used to assess the flow performance. The granular Bond number quantified from the inter-particle cohesion force using the multi-asperity model correlates well with the flow function coefficient. The lower values of standard error of prediction (0.04–0.10) for flow function coefficient of size segregated wheat flours and (0.03–0.19) flour blends indicate that the developed model agreed well with the experimental measurements. It was established that, the variations in the surface chemical composition of flour particles have a significant impact on the flow behavior of fine flours. The flow function coefficients of blends of size segregated flours can be predicted from ternary diagrams developed based on the model, and these predictions matched well with the experimental measurements. The model developed in this study will be useful to increase the throughput during size separation of wheat flours and also to assess the flow behavior of wheat flour blends.

1. Introduction

The end product of the wheat milling process is classified as flour in which "not less than 98 percent of the flour passes through a cloth having openings not larger than those of woven wire cloth designated 212 μm (No. 70)" (U.S. Code of Federal Regulations CFR, 2013). To manage the bulk flow of these micron sized flour particles, milling industries rely on the empirical knowledge and technical knowhow of the mill operators. Due to differences in particle cohesion, a significant loss in throughput is observed when sieving soft wheat flour in comparison to that of hard wheat flour (Neel and Hoseney, 1984a). Several characteristics of wheat flour have been considered to discuss these differences in flowability, such as cohesiveness, particle size, and the particle physical and chemical composition (Neel and Hoseney, 1984a, 1984b; Siliveru et al., 2016b). With the "inherently complex" nature of the granular materials, the particulate processes remain exceedingly difficult to model, design, and control (Andreotti et al., 2013). This complex and diverse bulk-scale behavior originates from contact and non-contact interactions among particles and their surroundings, thus the particle-scale interactions are difficult to resolve (Capece et al., 2015).

Due to the heterogeneity and anisotropic nature of the wheat flour, many published studies stressed the need for understanding the flowability issues of the wheat flours during storage and processing operations (Teunou et al., 1999; Landillon et al., 2008). Given that uniform flowability of flour is essential for better process control, there has been devoted efforts on this topic with most studies focusing on the effect of moisture content (Kamath et al., 1994; Teunou et al., 1999; Iqbal and Fitzpatrick, 2006; Landillon et al., 2008), particle size distribution (Neel and Hoseney, 1984a, 1984b; Landillon et al., 2008), and wheat class (Landillon et al., 2008; Bian et al., 2015). But, these studies omit the underlying mechanisms responsible for poor flow behavior of cohesive finer flour particles such as the cohesive forces that exist between the finer particles. Most importantly, the effect of surface chemical composition on the flow behavior of wheat flour is not a well understood phenomenon. The differences in chemical composition may lead to molecular bonding forces due to the formation of non-covalent hydrogen bonds, chemical links, or liquid fat bridges (Landillon et al., 2008).

In general, to assess or predict the flowability, flow function

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coefficient (ff_c) is the commonly used parameter that is determined by shear analysis. Mathematically modeling ff_c is limited to coarse powders (particles of 120 μm size or more). For coarse powders, bulk density is the criterion used for model development and is used extensively in assessing the gravity induced flows (Shultz, 2008). The same approach cannot be adapted for fine powders, because the inter-particle cohesive forces are highly dependent on the fundamental particle characteristics. For fine powders, the concept of Bond number introduced by Capece et al. (2015) allowed the prediction of flowability from the particle parameters such as particle size, surface roughness (asperities), surface energy, and density. For fine, dry, and uncharged particles, van der Waals force is dominated compared to the other forces like liquid bridging and mechanical interlocking (Castellanos, 2005). Because the van der Waals force can be orders of magnitude greater than particle weight; the ratio of which is predominantly referred to as granular Bond number (Capece et al., 2015). As the granular Bond number can be approximated from the measurable particle properties, an attempt was made in this study to propose a model for predicting the flow behavior of fine flour powders using the particle physical and chemical characteristics. In this study, the model was developed for wheat flour because the particle size of wheat flour is less than 120 μm and could be categorized as fine powder.

2. Theory and modeling of wheat flour flowability

2.1. Development of granular bond number for modeling of flour flowability

For wheat flour particles in close contact, their interparticulate interaction depends on molecular forces due to differences in chemical composition, capillary, electrostatic, and van der Waals (vdW) forces. During the model development, it was assumed that the sieving process happens in a controlled atmosphere (at constant r.h conditions and temperature). Therefore, the capillary forces between the particles were neglected. The electrostatic forces were known to be of tertiary importance and about 10 times weaker than vdW forces under typical dry atmospheric conditions (25–50% r.h) (Podczeck, 1998). Thus, during the model development, the discussion of forces was restricted to molecular interactions and vdW forces. The dipole-induced attraction between the constituent molecules (molecular interactions) from two interacting particles originates the vdW forces. The magnitude of these forces depends on particle characteristics such as; particle size, geometry, surface roughness, surface energy, and surface chemistry. Fine particle size flour, i.e. ~100 μm and smaller, can cause severe agglomeration resulting in non-ideal flour flowability (cohesive behavior) (Castellanos, 2005).

Therefore, due to the dominance of vdW forces for fine flours, in this study, the expression for cohesive force was developed by modifying the Rumpf cohesion model (Eq. (1)) proposed by Chen et al. (2008). This modified model also considers the non-contact interaction between two particles separated by distance H_0 and the contact forces between particles and asperities (Capece et al., 2015).

$$F_{cohesion} = \frac{A}{12z_0^2}\left(\frac{d_p}{2\left(H_0/z_0\right)^2} + \frac{3d_{asp}d_p}{d_{asp} + d_p}\right) \quad (1)$$

where A is Hamaker constant (J), Z_0 is the inter atomic equilibrium distance assumed to be 0.4 nm (Chirone et al., 2016), d_p is the particle diameter (m), H_0 is the separation distance (Capece et al., 2015), and d_{asp} is asperity diameter (m). The first term within the parenthesis on the right hand side of Eq. (1) accounts for the non-contact force between two particles separated by distance H_0, whereas the second term accounts for the contact forces between the particles.

To determine the particle's overall cohesiveness, a multitude of other body and surface forces must be considered along with the force of cohesion. In sieving and other dynamic processes, the force of gravity (W_g), a competing force to vdW force is most relevant and applicable in all the unit operations. To account for W_g, a dimensionless parameter known as the granular bond number (Bo_g) (which is described as the ratio of cohesive force to the non-cohesive forces (W_g)) is used to quantify the interparticle cohesion (Eq. (2)) (Castellanos, 2005).

$$Bo_g = \frac{F_{cohesion}}{W_g} \quad (2)$$

The Bond number concept used in this study, has been shown to correlate well with other bulk-scale flour properties such as bulk density (Yu et al., 2003; Capece et al., 2014), angle of repose (Jallo et al., 2011), and flow function coefficient (Huang et al., 2014; Capece et al., 2015). Due to the good correlation between these two parameters, a formal relationship can be established using the empirical expression as shown in Eq. (3).

$$ff_c = \alpha\left(Bo_g\right)^{-\beta} \quad (3)$$

The power law relationship (Eq. (4)), has also been observed for angle of repose (Jallo et al., 2011), powder bed porosity (Yu et al., 2003; Capece et al., 2014), and flow function coefficient (Huang et al., 2014; Capece et al., 2015). The parameters α and β used in the model (Eq. (3)) are material independent, since Bo_g takes into account all the relevant material properties (Capece et al., 2015).

2.2. Adjustment of granular bond number for developing a model for flour blends

To explain the flow behavior of flours blends, Eq. (3) was further extended to blended flour (ternary mixture prepared by mixing different particle size flours) containing three different particle sizes (75–106, 45–75, and <45 μm). The relationship between the flow function coefficient and Bond number of the flour mixture was established using the equation below:

$$ff_{c,Mix} = \alpha\left(Bo_{g,Mix}\right)^{-\beta} \quad (4)$$

Since, the Bond number of individual sized flours was determined by the interaction between the two particles of similar material (i.e. material having same physical, surface, and chemical properties), the Bond number of a multicomponent mixture must account for all the possible interactions of all the particles in contact. Thus, the Bond number of a mixed system is defined as the weighted harmonic mean of the granular Bond number between three components (i, j, and k) (Eq. (5)).

$$Bo_{g,Mix} = \left(\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{N}\frac{w_{ijk}}{Bo_{g,\,ijk}}\right)^{-1} \quad (5)$$

w_{ijk} represents the weighting function and can be determined using the fractional surface area (f_{SA}) of the particles in close contact and calculated using Eq. (6).

$$w_{ijk} = f_{SA,i}f_{SA,j}f_{SA,k} \quad (6)$$

The fractional surface area was calculated based on the ratio of Sauter mean diameter surface area to the particle diameter surface

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