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Flow properties and inter-particle forces in fuel powders

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ABSTRACT

This work studied the mechanical properties of a series of industrial fuel powders: bituminite, lignite, and petroleum coke. Sieved cuts of these powders were assessed and the flow properties of each sample were used to calculate tensile strengths as functions of consolidation stress. In addition, BET surface areas and dispersive surface energies were estimated from surface energy analysis. To analyze the bulk flow properties of these fuel powders in terms of micro-contact mechanics, the fundamentals of fuel powder adhesion and consolidation were reconsidered based on the "stiff particles with soft contacts" model proposed by Tomas. In the present work, a multi-contact concept was introduced to account for the irregular shapes of actual particles. This modified model was based on elastic–plastic contact deformation theory and was employed to describe the contact between rough particles and to estimate the associated inter-particle forces. The results were used in conjunction with the Rumpf approach to relate the isostatic tensile strength to the degree of consolidation. Applying average values for the powder compressibility parameters allowed the model to be used for predictive purposes, and an acceptable level of agreement was found between predicted and measured tensile strengths.

Introduction

Because of increasing demands for energy, entrained-flow carbon gasification is undergoing rapid industrial utilization around the world. This technology is characterized by large scale production, high efficiency, and clean emissions (Dai et al., 2008; Gong et al., 2014; Guo et al., 2007). However, to obtain suitably efficient carbon conversion, entrained-flow gasifiers operate with powdered fuels consisting of fine particles, such that 90% of the powder mass is made of particles smaller than 100 μm in diameter (Liu et al., 2016; Xiong, Aramideh, & Kong, 2013; Xiong, Aramideh, Passalacqua, & Kong, 2015; Xiong, Xu, Ramirez, Pannala, & Daw, 2016). The handling and storage of fine fuel powders lead to several well-known problems in process and storage equipment, including bridging, channeling, and fluctuating flow rates (Liu et al., 2015; Lu, Guo, Gong, Cong, & Dong, 2011; Lu et al., 2012). These phenomena originate from the strong cohesiveness resulting from various inter-particle forces (Bruni, Lettieri, Newton, & Barletta, 2007; Landi, Barletta, & Poletto, 2011; Rietema, 1973; Tykhoniuk et al., 2007). In the case of dry powders at ambient conditions, the adhesive forces can be primarily attributed to attractive dispersion forces such as van der Waals forces.

Inter-particle adhesive forces will vary with the extent of particle–particle contact during consolidation. In particular, in the case of dry powder, the direct solid–solid interactions can be modified by irreversible inter-particle contact deformation at the solid material surface. This phenomenon, together with particle spatial reorganization, largely determines the pre-consolidation flow properties on the bulk level. In principle, there are four essential deformation effects associated with particle–surface contacts, and their force–displacement behaviors can be summarized as follows (Tomas, 2003).

(1) Elastic contact deformation, which is reversible, independent of deformation rate and consolidation time effects and valid for all particulate solids.
(2) Plastic contact deformation with adhesion, which is irreversible and also deformation rate and consolidation time invariant.
(3) Viscoelastic contact deformation, which is reversible and dependent on both deformation rate and consolidation time.
(4) Viscoplastic contact deformation, which is irreversible and dependent on both deformation rate and consolidation time.

During slow "frictional" flow, for which the consolidation is time invariant, elastic and plastic deformations are dominant. Several

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Nomenclature

A_{el}	Elastic deformation area (m^2)
A_K	Total deformation area (m^2)
A_{pl}	Plastic deformation area (m^2)
$a_{F=0}$	Minimum intermolecular distance (m)
C	Cohesion (Pa)
$C_{H,sls}$	Hamaker constant (J)
d_s	Sauter diameter (m)
d_v	Volume diameter (m)
F_c	Adhesion force between two contact asperities (N)
F_H	Adhesion force of single contact (N)
F_{H0}	Adhesion force without contact deformation (N)
F_N	Normal force of single contact (N)
h_K	Center approach of two asperities (m)
K	Consolidation coefficient
K_a	Contact area coefficient
N	Compressibility index
N_C	Micro-contact number
P_f	Micro-yield strength of contact (Pa)
P_{vdw}	Attractive van der Waals pressure (Pa)
R^*	Asperity size (m)

Greek letters

γ^d	Dispersive surface energy (J/m^2)
E	Porosity
ε_0	Porosity of loose packing
κ_p	Plastic contact repulsion coefficient
$\rho_{b,0}$	Powder bulk density at negligible consolidation (kg/m^3)
ρ_M	Material density (kg/m^3)
σ	Normal stress (Pa)
σ_0	Isostatic tensile strength of unconsolidated powder (Pa)
σ_1	Major principal stress for steady-state flow (Pa)
σ_2	Minimum principal stress for steady-state flow (Pa)
σ_c	Unconfined yield strength (Pa)
σ_N	Pre-consolidation stress (Pa)
$\sigma_{t,iso}$	Isostatic tensile strength (Pa)
τ	Shear stress (Pa)
φ_i	Angle of internal friction (deg)
φ_{st}	Stationary angle of internal friction (deg)
ω	Work of adhesion (J/m^2)

papers have dealt with the estimation and characterization of the flow properties of fine powders, starting from the particles' physical properties and considering the contact micro-mechanics. Rumpf, Sommer, and Steier (1976) developed the first constitutive model describing the linear increases in inter-particle adhesive forces with the applied normal load, based on deformation theory. In addition, Molerus (1975, 1978) developed a plastic deformation theory for particles. However, in both works, the particle deformation was considered purely plastic.

To define the detachment force in the case of two isotropic, stiff, mono-disperse mineral particles interacting with an adhesive soft contact, it is necessary to identify a sequence of major steps. These include the particle approach, particle loading, elastic–plastic deformation of the particles that results in system consolidation, and system unloading that produces permanent contact flattening. Based on the above analysis, Medhe, Pitchumani, and Tomas (2005) and Tomas (2001, 2004a, 2004b) amended the perfect plastic contact deformation theory suggested by Molerus (1975, 1978) and Rumpf et al. (1976) by incorporating elastic–plastic contact deformation. This approach takes into account the particle contact force equilibrium between attraction and elastic and plastic repulsions. The adhesion model introduced by Tomas incorporates Hertz (1882) contact theory while developing the aspects of the model that deal with the extent of elastic and plastic deformations that the particles undergo. The resulting "stiff particles with soft contacts" model and the associated contact force equilibrium suggested by Tomas successfully predict the inter-particle adhesive force effects, based on particle mechanics and basic material characteristics. However, the original Tomas model primarily focuses on a set of smooth, mono-disperse, and spherical particles. Real particles often exhibit surface asperities, and so an appropriate description of the contact point behavior requires that the particle radius should be replaced by the local curvature radius. In fact, it has been shown that experimentally measured adhesive forces are lower than theoretical values predicted by the model, due to the reduction in contact area resulting from surface roughness (Podczeck, Newton, & James, 1996).

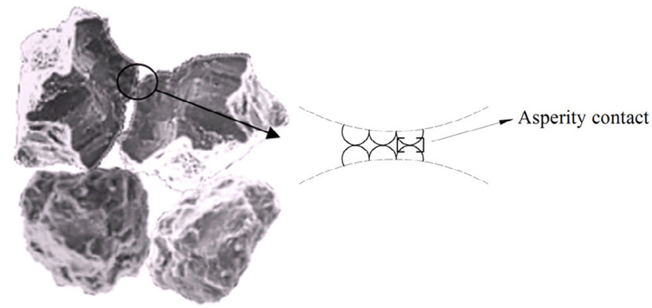

Fig. 1. A photographic image and diagram showing contact between rough particles.

Powder cohesiveness is difficult to control, alter, and model because it is affected by numerous factors, such as particle size, particle size distribution, particle shape, surface roughness, and surface energy, as well as other material properties, including hardness, elasticity, deformation, and even the presence of interstitial air. In the present work, the description of the flow properties of powders based on particle contacts was improved and the Tomas model was extended by introducing a multi-contact concept. In this framework, the effects of the particle surface roughness, number of micro-contacts, surface energy and material hardness on inter-particle forces and thus on bulk flow performance were studied and assessed. The aim of this work was to develop a model, inspired by the Tomas theory, to correlate and possibly predict the bulk flow properties of fuel powders made of very irregular, rough particles. This work also attempted to analyze these flow properties based on the force-response behavior of rough surfaces with evenly distributed mono-sized asperities. The results of this research should improve our ability to control processes using fuel powders and involving various operations, such as storage, discharge, and pneumatic conveyance.

Theoretical approach

Fig. 1 illustrates the contact between real-world fuel particles, which comprises asperity contacts. For the sake of simplicity, it is assumed that the individual asperities are evenly distributed on the particle surfaces and that all asperities can be model as spherical caps having the same radius of curvature. The rational for these assumptions is discussed in detail in Section 'Asperity size and micro-contact number'.

According to Tomas (2001), rough particle contact mechanics can be explained using a typical force–displacement diagram, as shown in Fig. 2. In contrast to the Tomas approach, the present work assumes contact between more than a single asperity, with the number of contacts represented by N_c. Fig. 3 summarizes the pres-

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