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# Bulk flow properties of fly ashes at ambient and high temperature

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ABSTRACT

The bulk flow properties of four different fly ashes were assessed at ambient temperature and at 500 °C, using a high temperature annular shear cell. These powders all resulted from industrial processes and had similar chemical compositions but different particle size distributions. Applying a high temperature was found to increase the powder cohesion, with this effect being more significant in the case of the sample with the highest proportion of fines. To better understand the effect of temperature on the bulk flow properties of these materials, a model previously proposed by some of the authors was used to correlate the powder isostatic tensile strength with the interparticle forces and microscale particle contact structure. This model combines the continuum approach with description of particle-to-particle interactions. A comparison with experimental data indicated that the effects of consolidation and temperature on the tensile strength of the fly ashes were correctly described by the model. This theoretical approach also elucidates the mechanism by which the temperature affects the bulk flow properties of fly ashes through modifications of the microscale interparticle contacts.



## Introduction

The flow properties of powders play a key role in industrial processing units and can significantly affect the production quality and the processing efficiency. Many industrial processing units, such as entrained-flow carbon gasification systems, also operate at high temperatures. In such systems, fly ash (fine particles representing the residue from coal combustion) is transported through the gasifier by flue gases. This ash is typically handled at high temperatures, and the powder cohesiveness may differ from that under ambient conditions.

Quantitative information regarding powder flow properties can be obtained from a variety of different test methods. Among these, shear testing is considered one of the most useful (Johanson, 1992; Maltby & Enstad, 1993; Schulze, 1994). The Mohr–Coulomb approach is often adopted in shear testing. In this process, the granular material is assumed to represent a continuum at the incipient failure condition. This approach helps to estimate the state of stress in solids handling and storage equipment (Fitzpatrick, Barringer, & Iqbal, 2004; Walker, 1966) and can be employed in the corresponding design procedures. Particle morphological characteristics (such as size and shape) and mechanical properties all affect the flow behavior of a powder, and Coulomb properties and the other related flow characteristics can modify the type and intensity of the interactions between particles by affecting contact mechanics. As an example, powder cohesiveness results from various interparticle forces, such as van der Waals, capillary, and electrostatic forces (Bruni, Lettieri, Newton, & Barletta, 2007; Landi, Barletta, & Poletto, 2011; Rietema, 1973; Tykhoniuk et al., 2007). Even dry powders, when electrostatic charging can be excluded, are affected by adhesion effects resulting from dispersive attractive interactions such as van der Waals forces.

It is important to characterize the flow properties of powders under conditions relevant to industrial processes, including at high temperature (Chirone, Barletta, Lettieri, & Poletto, 2016; Kanaoka, Hata, & Makino, 2001). Previous studies on the effect of temperature on fluidization have included bed expansion measurements (Lettieri, Newton, & Yates, 2002; Xie & Geldart, 1995;) and bed collapse tests (Bruni, Lettieri, Newton, & Yates, 2006; Lettieri, Newton, & Yates, 2001), and have shown changes in the fluidization behavior with temperature. These phenomena cannot

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**Nomenclature**

| | |
|---|---|
| $a$ | Parameter in Eq. (10) |
| $a_{F=0}$ | Minimum intermolecular distance (m) |
| $C$ | Cohesion (Pa) |
| $d_s$ | Mean Sauter diameter (m) |
| $d_v$ | Volume diameter (m) |
| $d_{10}$ | 10th percentile particle size (m) |
| $d_{50}$ | 50th percentile particle size (m) |
| $d_{90}$ | 90th percentile particle size (m) |
| $F_{ji}$ | Adhesion force between two contact particles (N) |
| $F_{H0}$ | Adhesion force without contact deformation (N) |
| $F_N$ | Normal force at a single contact (N) |
| $f_j$ | Number fraction of particle $j$ |
| $h$ | Consolidation coefficient |
| $h_a$ | Contact area coefficient |
| $k_0$ | Coordination number in a uniformly-sized particle bed |
| $k_{ji}$ | Coordination number of particle $j$ in contact with particle $i$ |
| $P_f$ | Material yield strength (Pa) |
| $P_{vdW}$ | Attractive van der Waals pressure (Pa) |
| $R^*$ | Asperity size (m) |
| $r_j$ | Particle radius (m) |
| $S$ | Particle surface |
| $s_j$ | Fractional area of particle $j$ |

*Greek letters*

| | |
|---|---|
| $\gamma^d$ | Dispersive surface energy (J/m$^2$) |
| $\varepsilon$ | Voidage |
| $\varepsilon_0$ | Voidage of loose packing |
| $\kappa_p$ | Plastic contact repulsion coefficient |
| $\rho_b$ | Powder bulk density (kg/m$^3$) |
| $\rho_M$ | Material density (kg/m$^3$) |
| $\sigma_0$ | Isostatic tensile strength of unconsolidated powder (Pa) |
| $\sigma_1$ | Major principal stress for steady-state flow (Pa) |
| $\sigma_2$ | Minor principal stress for steady-state flow (Pa) |
| $\sigma_c$ | Unconfined yield strength (Pa) |
| $\sigma_{t,iso}$ | Isostatic tensile strength (Pa) |
| $\tau$ | Shear stress (Pa) |
| $\varphi_i$ | Angle of internal friction (°) |
| $\varphi_{st}$ | Stationary angle of internal friction (°) |
| $\omega$ | Work of adhesion (J/m$^2$) |
| $\omega_j$ | Component mass fraction |

be fully explained by fluid dynamic forces alone. The most general approach to understanding these effects assumes that cohesive interparticle forces become relevant when their intensity is comparable to the effects of particle mass. Interparticle forces have often been directly measured (Forsyth, Hutton, & Rhodes, 2002; Tanaka, Komagata, Tsukada, & Kamiya, 2008), although this is a complex procedure that requires a statistically significant quantity of data. Carrying out such measurements at high temperatures also increases the level of complexity. Alternatively, it is possible to determine bulk properties at both ambient and high temperatures and to correlate changes in cohesiveness with variations in the interparticle forces (Kojima & Elliott, 2012, 2014; Quintanilla, Castellanos, & Valverde, 2001). In particular, the effect of temperature on interparticle forces can be direct, such as when temperature determines the formation of a liquid phase responsible for the formation of liquid bridges. It is also possible to assess changes in forces that are due to temperature-independent interactions, such as van der Waals forces, by changing the contact properties, including material hardness. Interestingly, few studies have addressed the empirical evaluation of powder flow properties at high temperatures (Hurley, Mukherjee, & Mann, 2006; Kamiya, Kimura, Yokoyama, Naito, & Jimbo, 2002; Smith, Haddad, & Ferer, 1997) even though experimental results have shown that the unconfined yield strength of powders increases with temperature. The high temperature annular shear cell (HT-ASC) developed at the University of Salerno has been demonstrated to be suitable for measurements of powder yield loci up to 500 °C (Tomasetta, Barletta, & Poletto, 2011; Tomasetta, Barletta, & Poletto, 2013). Analysis of such high temperature results has revealed that the proper treatment of data requires accounting for the plastic deformation of contact points (Macrì, Poletto, Barletta, Sutcliffe, & Lettieri, 2017). More recently, Chirone et al. (2016) studied the flow properties of ceramic powders characterized by various narrow particle size distributions, using the HT-ASC. In this prior work, plastic behavior of the material at the contact points was introduced into the model evaluation process to explain the experimental observations. Assuming perfect plastic deformation of contacts is one means of simplifying the hypothesis and very good correlations between experimental results and theoretical predictions were obtained using the elastic–plastic deformation theory of contacts developed by Tomas (2001, 2004a, 2004b) in work with real systems including rough particles (Liu, Lu, Poletto, Guo, & Gong, 2017) and high temperatures (Tomasetta, Barletta, & Poletto, 2014). However, the majority of these studies were performed assuming mono-sized particulate systems, while industrial-grade powders are often characterized by wide particle size distributions (Lu, Guo, Gong, Cong, & Dong, 2011; Lu et al., 2012; Liu et al., 2015).

The present work attempted to quantitatively describe the fundamental effects of temperature on the incipient flow behavior of fly ash powders, and to compare the effect of different size-cuts on the bulk flow properties. To better assess these factors, an HT-ASC was used to study the flow properties of four fly ash samples with similar compositions but different particle size distributions (PSDs). Powder flow properties were measured at ambient temperature and at 500 °C, a temperature at which the effect of temperature on the material hardness was demonstrated. A model developed by Liu, Lu, Poletto, Guo, and Gong, (2017) was used to predict the effect of temperature on the isostatic tensile strengths of the powder samples. According to this model, the continuum approach and the particle–particle interaction description can be correlated with one another while considering the powder's isostatic tensile strength, even in systems characterized by a wide PSD.

## Material and methods

### High temperature annular shear cell

An HT-ASC apparatus, previously developed and built at the University of Salerno, was used to measured the powder bulk flow properties at ambient temperature and at 500 °C. Fig. 1 presents a schematic diagram and photographic images of the apparatus. The shear cell in this unit had an internal volume of 95 cm$^3$ (60 mm inner diameter, 120 mm outer diameter, and 10 mm height). The HT-ASC operated on the same work bench of the original Schulze ring shear tester. Electric heaters were located at the bottom ring and in the lid to heat the powder sample in the cell to the desired temperature. Further details regarding this unit have been previously reported by Tomasetta et al. (2011). Experimental trials were carried out with the same powder specimen to measure three different yield loci and in turn to obtain a flow function with four points. As well, the major principal stress was determined over the range of 6.5–20.0 kPa. Normal stress values were employed so as to approach a consolidation state approximating that of consolidated