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Original Research Paper

Consideration of the stress dependence of the bulk density in silo storage of dusts from dry off-gas cleaning

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ABSTRACT

In this study the influence of the consolidation stress on the bulk density of dusts separated from the off-gas of a broad variety of industrial processes was investigated. With the exception of very small values of the stress this dependence can be approximated very well by a simple function. One coefficient in this function correlates very well with the bulk density measured according to EN ISO 60, while the other coefficient shows a good correlation with a function, combining several dust properties. Using this approximation function equations for the vertical stress and bulk density in the shaft of a cylindrical silo as a function of the distance from the surface were derived. The results for the vertical stress and the mass of the bulk obtained with these equations were compared with those acquired on the basis of Janssen's equation assuming constant bulk density according to EN ISO 60 and a constant average bulk density. Up to a certain distance from the surface of the bulk the values for the stress and for the mass were between the results obtained by the two variants with constant bulk density, whereas for greater distances the resulting values were higher.

1. Introduction

Dust storage silos are an important but often a somewhat neglected part of dry off-gas cleaning systems. Besides the requirement for the stability of the silo structure, the main issues in silo design are its storage capacity and design to avoid flow problems. A method for proper design of the discharge was developed by Jenike [1] which is still well used [2,3]. The storage volume of the silo is a mere question of geometry, while the mass storage capacity involves the bulk density, ρ_b, of the material. For the measurement of the bulk density of granular material several standards are available, for example, EN ISO 60 [4], EN 1236 [5], ISO 697 [6] or ASTM D6393 [7]. For a constant bulk density the mass of the bulk results from the product of the bulk density and the volume stored. However, variations in bulk density can have a significant effect on the mass of material kept in the storage space [8]. For fine-grained material the assumption of a constant bulk density is only a rough approximation. A significant increase of the bulk density with increasing consolidation stress has been reported for the dusts from various dry off-gas cleaning systems [9–12].

The classical method to calculate the stress in the vertical section of a silo was developed in 1895 by Janssen [13]. An annotated translation of this paper is also available [14]. Janssen considered a slice element of infinitesimal height, *dz*. With the assumptions of constant vertical stress, σ_v, acting across the cross-section, constant bulk density, ρ_b, constant wall friction angle, ϕ_w, and the constant lateral stress ratio $K = \sigma_h/\sigma_v$, the equilibrium of forces in *z*-direction results in a differential equation for the vertical stress (Eq. (1)):

$$\frac{d\sigma_v}{dz} + \sigma_v \cdot K \cdot \frac{U}{A} \cdot \tan\phi_w = g \cdot \rho_b \tag{1}$$

This first order differential equation can be solved analytically. When the stress on the top surface of the bulk material is zero ($\sigma_v = 0$ at $z = 0$), the well-known "Janssen equation" (Eq. (2)) yields:

$$\sigma_v = \frac{\rho_b \cdot g}{K \cdot \tan\phi_w} \cdot \frac{A}{U} \cdot \left(1 - \exp\left(-K \cdot \tan\phi_w \cdot \frac{U}{A} \cdot z\right)\right) \tag{2}$$

In currently applied engineering methods a homogeneous density of the material throughout the silo is assumed. Depending on the design method different values for this mean bulk density are taken, for example, $\rho_b = (\rho_{b,\min} + 2 \cdot \rho_{b,\max})/3$ or values fixed a priori for each material [15]. In Eurocode 1 [16], coefficients are used to consider the variability of the bulk properties. In silo design, the

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Nomenclature

A	cross section of the silo shaft (m^2)
B	material specific constant in the approximation function (kg/m^3)
c	material specific exponent (constant) in the approximation function (–)
d_{50}	mass median of the size distribution (μm)
d_{90}, d_{10}	particle size with 90% (10%) of the particle mass smaller (μm)
$E1$ to $E5$	exponents in function F (–)
F	empirical function combining the variables influencing the exponent c (–)
ff_c	flowability (–)
g	acceleration of gravity (m/s^2)
h, k, n	constants in various approximation functions for the bulk density (–)
K	stress ratio (–)
m_b	mass of the bulk (kg)
U	inner circumference of the silo shaft (m)
z	distance from the surface of the bulk (m)
ρ_b	bulk density (kg/m^3)
σ	normal stress (Pa)
σ_1	major principal stress (Pa)
τ	shear stress (Pa)
ϕ_w	wall friction angle (°)
φ_{eff}	effective angle of internal friction (°)

Indices

0	reference state
h	horizontal
v	vertical
max	maximum
min	minimum

problem of the stress dependence of the bulk density can be handled by a pointwise input of density data at different stress values [17]. This method is used e.g. by the calculation tool "Silo Stress Tool" [18].

For the approximation of the dependence of the bulk density of compressible granular material on the vertical stress various types of equations have been applied. In one study [19] a parabolic relationship ($\rho_b = \rho_{b,0} + h \cdot \sigma^{0.5}$) was adopted, while the linear regression ($\rho_b = \rho_{b,0} + k \cdot \sigma$) resulted in a somewhat reduced match. $\rho_{b,0}$ is the bulk density at a vertical stress of zero. A more flexible equation with a variable exponent was used in another study [20]. In a slightly different approach the approximation function ($\rho_b = \rho_{b,0} \cdot (1 + \sigma)^n$) was used [21,22]. Common to all these equations is that at a vertical stress of zero the bulk density is equal to $\rho_{b,0}$. A differently structured equation (Eq. (3)) for the description of the effect of the compressibility on the bulk density was described in another study [8]. There σ_1 is the major principal stress and c is a constant in the range between zero and one. This equation is hardly valid at very low stress values because at zero stress the value of the bulk density would also be zero.

$$\rho_b = \rho_{b,0} \cdot \left(\frac{\sigma_1}{\sigma_{1,0}}\right)^c \tag{3}$$

In contrast to the bulk density, the wall friction angle was found to be quite constant for many dusts, especially at values of the wall normal stress higher than 2 kPa [9–11]. The lateral stress ratio K is also essentially independent of the vertical stress [16]. It lies typically in the range of 0.4–0.5 [2].

The aim of this work is to describe the dependence of the bulk density on the consolidation stress for dusts collected in various dry de-dusting systems by a function instead of a pointwise relation and, moreover, to investigate the impact of this dependence on the consolidation stress and the mass of the bulk in dust silos.

2. Materials and methods

The dust samples investigated were collected from the de-dusting system of various industrial plants (combustion plants, steelmaking plants (carbon steel), non-ferrous metallurgical plants and mineral plants). Approximately 2 dm^3 of dust were collected at the dust discharge outlet of each de-dusting system. The volumes of the dust samples were reduced to an amount suitable for the various laboratory tests using sample dividers which were applied repeatedly (Haver RT 12.5, Quantachrome Micro Riffler).

The particle size distribution of the dust samples was measured using a Sympatec HELOS/RODOS laser diffraction instrument with dry sample dispersion. The instrument was checked with a Sympatec SiC-P600'06 standard with a target value for the mass median diameter d_{50} of 25.59 μm and an acceptable range of 24.82–26.36 μm. The measured value for the d_{50} was 25.62 μm. The spread of the particle size distribution was calculated by d_{90}/d_{10} and the relative span was calculated by $(d_{90} - d_{10})/d_{50}$.

The bulk density of the dust samples was determined according to EN ISO 60 [4]. 120 cm^3 of dust stored in a funnel flows by means of gravity into a coaxial 100 cm^3 measuring cylinder when the bottom cover of the funnel is removed. The volume of the certified measuring cylinder is 100 ± 0.5 cm^3. The excess material is removed from the top of the cylinder by drawing a straight blade across the top of the measuring cylinder.

The bulk density of the dust samples under various values of the consolidation stress σ_1 was determined using a RST-XS ring shear tester with a 30 cm^3 shear cell from Schulze. The test procedure was conducted in accordance with ASTM D 6773 [23] at four values of the normal stress (600 Pa, 2000 Pa, 6000 Pa and 20,000 Pa). For ring shear testers a good reproducibility of the measurements is reported [24]. The calibration of the shear tester was verified at a normal stress of 3000 Pa at pre-shear using the certified reference material BCR-116 (Limestone Powder from the Community Bureau of Reference), which was also used in a round robin test on ring shear testers [24]. The measured values of the shear stress were in the range of the reported mean shear stress $\tau_m \pm 0.6$ times the reported standard deviation, s. The average bulk density measured was 897 ± 6 kg/m^3. A comparison with the results obtained in the round robin test is not possible because the values for the bulk density were not published. The wall friction angles were also determined with the ring shear tester, using a wall friction shear cell instead. In this cell, the bottom ring is formed by a sample of the wall material tested.

Results from shear tests with dusts from various other industrial processes (sinter plants, blast furnaces and cement mills) have been published recently [9–12]. From these results the parameters of the approximation equations for the bulk density were also derived.