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Mass flow during unloading of agricultural bulk materials from silos depending on particle form, flow properties and geometry of the discharge opening

Jochen Mellmann *, Thomas Hoffmann, Christian Fürll

Leibniz Institute for Agricultural Engineering Potsdam, Department of Postharvest Technology, Max-Eyth-Allee 100, 14469 Potsdam, Germany

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ABSTRACT

Knowledge of the grain and powder mass flow in silos and hoppers during free outflow is important for some tasks in installation planning. It can be expressed by the Froude number as a dimensionless similarity indicator. The objective of the investigations is to record the influence of the flow properties and in particular of the particle form of crushed grain products. In the pertinent literature the particle form is generally stated as less significant by comparison with the particle size. As hardly any results are available for crushed grain products so far, experiments were conducted with two particle size fractions in the range of x = 0.3…0.8 mm that possess slightly cohesive or cohesionless properties. The particle form was characterized by the ratio of particle length to particle width (elongation). It is evident in all results that the deviation from the spherical shape influences the particle properties. In the particle fractions examined, the flowability according to Jenike decreases as the elongation increases. The Froude number determined during the unloading experiments decreases with strong correlation as the elongation values increases, in line with the reduction in flowability of the bulk material samples.

1. Introduction

For some plant installations, knowledge of the mass flow in [kg/s] or [t/h] is significant as a matter of principle. For example in dosing processes the feed flow of the bulk material to the dosing organ must be coordinated. The dosing mass flow that is to be regulated by a dosing organ can never be greater than the mass flow from free feed flow. The feed mass flow is critically determined by the outlet geometry of the silo and the flow properties of the respective bulk material. Knowledge of the flow properties of bulk materials is therefore a key basis for planning processes and dimensioning machinery and equipment for handling bulk material in nearly all areas of industry.

In the specific case under review here the subject bulk material was examined with the aid of proven shear testers and the interesting parameters – uniaxial compressive strength, the various angles of internal friction, the density and the wall friction angle – were determined. Knowledge of how the physical and material parameters influence the flow properties is important, especially for research, making it possible to design optimal and low-cost handling of bulk materials in further processing. These parameters also include the particle form, which is influenced above all by crushing. As few results on this aspect are available in the relevant literature, the following investigations were conducted.

2. State of research

The mass flow at the silo discharge depends on a variety of influencing variables; hence, it is almost impossible to exactly predict the flow rate [1,2]. For it, different approaches have been developed in literature, see for example [3–6]. Alongside the geometrical parameters of the silos, it is the flow properties of bulk material that exert the largest influence on the mass flow when product is unloaded from silos. These properties, together with particle size distribution, moisture content, temperature and chemical composition, are also influenced by the particle form and time of storage [7]. While in the case of coarse particles smooth and round particles generally flow better than rough particles and those deviating substantially from a spherical form, this cannot be said universally for cohesive bulk materials. In these above all the adhesive forces are crucial [1]. According to investigations by Schulze [8], the flow of fibrous and platelet-formed particles is all the poorer, the larger the ratio of particle length to particle thickness, the higher the coefficient of friction acting between the particles, and the lower the porosity. According to the results published in literature, the influence of the particle form is not uniform by comparison with the influence of the particle size. Studies by Emery [9] and Podczek et al. [10] revealed that the particle form of pharmaceutical products exerts a greater influence on their flowability than the particle size. On the other hand, the results obtained by Abhay [11] and Jaeda [12] show a dominant influence of the particle size. In nearly all these studies [9–12], a reduction of the angle of repose and the angle of internal friction and an increase in the flowability according to Jenike [13,14] were

* Corresponding author. Tel.: +49 3315699321; fax: +49 3315699849.
E-mail address: jmellmann@atb-potsdam.de (J. Mellmann).

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measured in line with the rise in the ratio of maximum to minimum particle dimension or roundness.

If the mass flow of bulk material flowing out of containers is used as a measure for the flowability, then according to studies by Lehmann [15] a dependence on the particle form factor ψ is obtained that is defined as the ratio of real volume to the volume of the smallest possible circumscribing sphere. The mass flow is all the greater, the more the form factor approaches the value 1. As the ratio of the smallest to largest particle dimension becomes higher, the mass flow on unloading from containers increases.

With the help of DEM modeling, the unloading mass flow can be determined as a function of the particle form as well [16]. Abstracted from their investigations Gonzales-Montellano et al. [17] stated, that the particle shape and the resulting geometric interlocking are important for predicting the flow pattern in a silo closer to the experimental observations. More recently, the DEM is increasingly used to model the flow and discharge of, both, non-cohesive and cohesive particles from hoppers and silos [16–19].

In view of the large number of influencing parameters, it is virtually impossible to predict the discharge mass flow precisely. Despite this, many authors suggest calculating the discharge mass flow with the help of equations from empirical or dimensional analysis studies [1,2]. For coarse-grained goods, the discharge mass flow is proportional to the bulk material density ρ_S, to the outflow diameter d and to a few adjustment factors k_i, which take into account for instance the hopper angle of inclination and the particle form as

$$\dot{M} \sim \rho_S, d, k_i \quad (1)$$

For circular discharge openings, Beverloo et al. [3] derived the following equation

$$\dot{M} = C \cdot \rho_b \cdot \sqrt{g} \cdot (d - k \cdot x)^{2.5} \quad (2)$$

The coefficients in Eq. (2) are given as C = 0.55 … 0.65 and k = 1.5 … 3.0. The term k x considers the solids-free region at the border of the outlet opening the thickness of which depends on the particle size x.

In the case of fine grained and cohesive bulk materials, the gas pressure or the pressure gradient dp/dz must also be taken into account [1,2] as

$$\dot{M} \sim \rho_S, d, k_i, \frac{dp}{dz} \quad (3)$$

3. Objective of the investigations

Out of the many factors influencing the mass flow of agricultural bulk material during unloading in addition to the silo geometry, this paper examines above all the flow properties and the particle form.

A whole series of results is available on the influence of the particle size, particle size distribution, moisture content of the product and storage duration on the flow properties, see for example [7]. However, hardly any results have been published on the influence of the particle form [20]. That is why the planned investigations were conducted with the following objectives:

- to analyze the parameters influencing the flowability of crushed grain products;
- to determine the flowability according to Jenike for the crushed grain species wheat, barley, oats and maize as a function of suitable form factors and their distribution parameters;
- to determine the discharge mass flow from a model container as a function of suitable parameters of the flowability and the particle form;
- to apply the Froude number as dimensionless similarity indicator for the functional connections examined.

4. Investigations

4.1. Experimental goods and form factor parameters

The experimental goods are wheat, barley, oats and maize in crushed and non-crushed form. Crushing was carried out with a hammer mill. It was to be expected that as a result of different consistencies of the grain species, particles with a broad spectrum of form factors would result. After crushing, two particle size fractions of 0.315 < x < 0.50 mm and 0.50 < x < 0.80 mm were selected for the investigations by screening (Table 1). It is to be expected that the larger fraction has cohesionless properties and that the smaller fraction retains slightly cohesive properties. The dry matter content was kept constant by climate control and was on average 88%.

The literature provides a whole series of suggestions for characterizing the particle form [21]. In the following investigations the elongation FF was selected as form factor

$$FF = \frac{a}{b} \quad (4)$$

which describes the ratio of particle length a to particle width b. For each sample 30 particles were measured. The median value $FF_{50;0}$, the modal value FF_h and the standard deviation $\sigma_{\zeta FF}$ were determined as distribution parameters of a logarithmic normal distribution of the form factor for the two particle size fractions. The logarithmic normal distribution was chosen because it could fit the experimental data well.

4.2. Experimental method

Before the unloading experiments, the flowability ff_c of the samples was measured with the help of shear tests (Table 1). For it, shear strength measurements were carried out with a ring shear cell according to Walker [22], see Fig. 1. The mass of the respective sample which was sheared inside the shear device was obtained from the volume and the compression level for the yield locus investigated. The performance of the experiment is sufficiently known and specified internationally, see for example [1,4].

For each sample, four yield loci were measured by varying the consolidation stress σ_1 in the range between 4000 Pa and 14,000 Pa. After it, the values of the compression strength σ_c were obtained from the yield loci. The flowability ff_c was then calculated for each yield locus as

$$ff_c = \frac{\sigma_1}{\sigma_c} \quad (5)$$

The measurements revealed the known tendency that the flowability increased in line with the consolidation stress σ_1 [1]. This

Table 1
Properties of the bulk materials and statistical values from the form factor distribution (logarithmic normal distribution).

Product	Sample no.	Mean particle size $\bar{x}$ [mm]	Form factor modal value FF_h [−]	Form factor median $FF_{50.0}$ [−]	Standard deviation of $FF_{50;0}$ $\sigma_{\zeta;FF}$ [−]	Flowability ff_c [−]
Wheat	1	0.4075	1.5	1.36	0.067	26.13
Wheat	2	0.65	1.5	1.58	0.114	36.51
Barley	3	0.4075	1.5	1.50	0.126	10.78
Barley	4	0.65	1.5	1.68	0.138	22.50
Maize	5	0.4075	1.5	1.52	0.085	9.66
Maize	6	0.65	1.3	1.42	0.070	44.36
Oats	7	0.4075	1.1 and 1.5	1.85	0.179	10.58
Oats	8	0.65	1.5 and 1.7	2.17	0.207	14.80