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Rheology of moist food powders as affected by moisture content

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ABSTRACT

Dynamic testing to determine rheological characteristics of moist food powders (semolina, coarse wheat flour, potato starch) was carried out using a powder rheometer of a new construction. The unique feature of the rheometer is that scale of shearing was confined to the thickness of shearing band of powder bed only. It was found that flow pattern of moistened samples was noticeably and diversely affected by both moisture content (varying in the range of 0–15% w/w) and shear rate. The observed changes showed statistical significance $p < 0.01$ in all trials carried out. What is noteworthy about the conducted research is that at some shear rate values, the shear stress of the bed reached the maximum for specific moisture content levels, irrespective of particle size of the bed. Such behavior may provide an indication of complex interference of different powder shearing mechanisms in the presence of moisture. For beds consisted of larger particles, shear stress values decreased considerably with increasing moisture content. To explain this, modeling of the shearing process with Discrete Element Method (DEM) was performed. The results obtained supported the idea that friction coefficients of particulate material were significantly reduced at higher moisture content of the powder bed in the whole range of shear rates applied.

1. Introduction

Powders or granular materials when flowing can be in different rheological state depending on the way the particles interact with each other. In rapid flow, the particles interact predominantly by short collisions and their energy is dissipated mainly due to their inelasticity. It is often assumed that particles in rapid flow are so energized that they show behavior similar to that of molecules in a gas or freely flowing fluid. Theoretical considerations concerning such flow regime are therefore usually based on the kinetic theory of gas and a general literature review on existing models is given by Tardos [24].

During slow or moderate flows, the particles are in contact for extended periods of time and the predominant mechanism responsible for energy dissipation is particles frictional sliding. The most important feature of the powder in the slow flow regime is that the bed behavior does not follow with a similarity to that of a solid or a fluid [13]. Owing to the complexity of such flows they received little attention and theoretical approaches to the flow mechanisms are diverse [15]. More experimental methods and results are therefore needed in order to validate theoretical achievements and some known analytical solutions making them more applicable to particulate powder flow.

Methods of experimental investigation of slowly flowing granular materials originated from basis conceptions of soil mechanics. They were extended and modified by Jenike [12] to apply mostly for the purpose of silo design. However, the Jenike shear tester may be an inappropriate method for testing granular materials of higher moisture contents [17]. Alternatively for such materials, a dynamic shear cell (a powder rheometer) can be used [13,24]. The shear process is realized in annular cell and the shear and normal stresses over a range of shear rate are measured. Powder rheometer is a valuable tool for measuring stresses in loosely compacted powder beds [2] for which Jenike [12] tester is not suitable. Although other methods of characterizing powder flow behavior at low stresses and under dynamic conditions have been reported [10,18,19,27], but for moist powders and continuous shearing rheometer has better control over the test conditions. However, similar to the techniques suggested by above authors, the continuous shearing provided by rheometer can be carried out at low normal stresses applicable to some industrial operations conditions, e.g. fluidization, mixing or pneumatic transport, as well as possibility to test powders in dynamic conditions. This provides better differentiation in flowability of powders processed in dissimilar packing states [6]. An example of this may be limestone powders modified with different hydrophobizing agents: stearic acid vapor and silicone solution [26]. Yield loci obtained for these powders (under high normal load) were almost the same as unmodified raw limestone powder. However, rheological characteristics of modified materials (obtained under low normal load) varied significantly between all the examined samples (Opaliński, Vogt, to be published).

As moisture content in a powder bed increases, the interactions between particles are strengthened usually by forming liquid bridges [9,29]. The cohesion properties of food powders are also dependent on

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their chemical and biochemical properties. Landillon et al. [14] found that starch and soluble pentosans may increase viscosity of liquid bridges, thereby increasing their strength. Soluble components of grains or seeds may lead to plasticizing of powder resulting in an increase in contact area and surface stickiness [23]. Fitzpatrick et al. [5] showed that the food powders with greater amount of amorphous lactose were more sensitive to absorbing moisture giving rise to lumping and caking problems. The complex behavior of moist food powders was also found by Ganesan et al. [7,8] for DDGS (Distillers Dried Grains with Solubles the main bi-product of ethanol production from non-fermentable maize residues). They found that flow function values for DDGS decreased with increasing moisture content (10 to 20%), but increased for 25 and 30% moisture content. Thus, above a certain moisture content, a lubricating effect of moisture is possible and an improvement in flow can be observed. This contradictory effect of moisture content on powder flowability is particularly significant for powders flowing under small values of normal load where flow conditions are not suppressed by overwhelming action of contact forces as in the case of powder sheared in Jenike shear tester.

A key factor affecting flow of powders (particularly food powders) is surface friction defined as the frictional resistance to bulk flow that includes both particle-particle and particle-wall interactions. Some early data [21] concerning flow of cohesionless bulk solids in a vertical converging channel showed that the particle-wall friction was more influential for the rate of flow than the angle of internal friction. Surface friction influences both wall and bulk solids properties as well as and handling conditions [1,20]. Humidity of the surrounding air or moisture content of bulk solid significantly influences the surface properties of solid particles and as a result also the surface friction but the way the moisture interacts with particle material is complex. This is firstly due to the capability of food materials to absorb water to some extent and secondly due to some biological changes that may occur inside the particle material in presence of water. Despite general awareness of the friction phenomena for powder flow [8] there is so far no quantitative data allowing prediction of the friction coefficient as a function of particles moisture content. This would provide a constructive approach to reflect and explain in quantitative terms the complex rheology of food powders and their flowability under various process conditions.

The aim of this work was (i) to show experimentally how moisture content affects the rheology of food powders, and (ii) to obtain computational values of friction coefficients of moistened food powders that provide agreement between measured and calculated results. The rheology of food powders was investigated by a new type of powder rheometer enabling a precise control and calculation of the velocity gradient in shear band of the examined powder bed. To obtain friction coefficients DEM modeling method was used and calculation were performed with PFC2D software (Itasca Consulting Group Inc.). Friction coefficients for both translational and rolling movement of contacting particles, as well as damping constants were considered and their changes with humidity and shear rate of the powder bed are given.

2. Materials and methods

2.1. Physical properties

The materials used were commercially available food powders: semolina, coarse wheat flour, common wheat-flour, potato starch and milk powder. Particle size distribution (PSD) for the powders was obtained using a Malvern Mastersizer 2000E laser diffraction analyzer. The powders were dispersed in isopropyl alcohol to allow for PSD measurement. The measured values of particle size are summarized in Table 1 and an example of the PSD for coarse wheat flour, potato starch and semolina are given in Fig. 1. More details on physical properties of the materials and the methods used to obtain them were given in earlier paper of the authors [17].

Table 1
Physical properties of studied powders.

Material	d_{50}* [μm]	d_{10}* [μm]	d_{90}* [μm]	$d_n = \frac{d_{90}-d_{10}}{d_{50}}[-]$
Semolina	288	118	517	1.39
Coarse wheat flour	140	106	189	0.60
Common wheat flour	62.5	28	97	1.10
Potato starch	24	13	37	1.01
Milk powder	111	44	239	1.75

* d_{50}, d_{10}, d_{90} are values of the particle diameter at 50%, 10% or 90% in the cumulative size distribution, respectively.

Hydration of materials was accomplished by direct addition of water to samples, plus mixing until a homogeneous consistency was obtained. In the case of highly dispersed food powders, e.g. potato starch or common wheat-flour, the moisturizing method entailed passing a stream of air of controlled humidity through the materials being mixed in the *V*-type drum mixer. This was a protracted process. To obtain higher moisture contents of the materials under investigation, it was necessary to keep mixing for many hours, as for example, it was found for the required final moisture content of common wheat-flour.

Moisture content usually applied in operations involving food powders varies in a rather broad range from 1 to 5% for milk powder, 10–15% for commercially available flours to 40–60% for pasta and bread processing. For this reason water content in current experiments was gradually increased until marked changes in rheological characteristics developed and this typically was observed for moisture contents not larger than 15–20%.

Moisture content was determined by weighing about a 5–7 g sample before and after drying at 70 °C. All examined samples were dried in laboratory vacuum heating chamber SPT-200 (ZUT COLECTOR, Poland). The drying and weighing procedure was repeated several times until constant mass of the sample was obtained.

2.2. Rheological measurements

The objective of this experimental investigation was to present and analyze the rheological characteristics of food powders as affected by moisture content. The rheological state that has been recognized as the most important from cognitive and practical point of view, was frictional flow realized at slow shear rates. In order to remain within the frictional flow regime it was necessary to carry out the experiments at shear rates as low as possible. The lowest stable rheometer speed was equal to about 5 rpm, i.e. approximately with blade tip speed of 2.5 cm s^{-1} and this value was a starting point for each experiment. The experiments were however carried out also at much higher shear

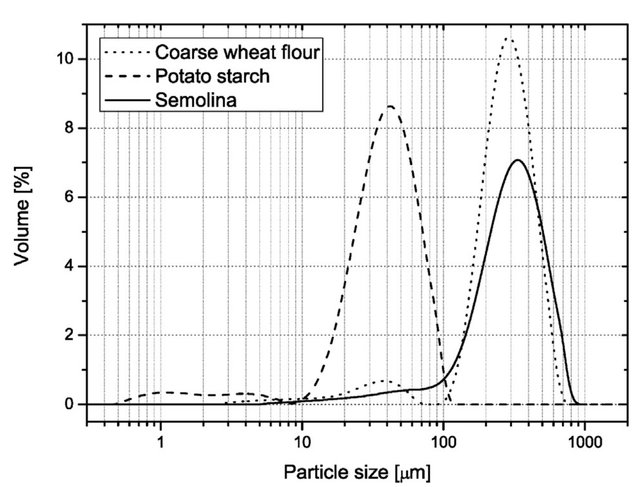

Fig. 1. Particle size distribution for coarse wheat flour, potato starch and semolina.