Analysis of modern methods for determining the dynamic friction of bulk materials

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Abstract. The coefficient of dynamic friction is investigated in widespread gravitational flows of granular materials of numerous technological processes. The calculation of dynamic friction is necessary in the study of shear flows, the behavior of the sediment layer on an inclined plane, tracking the sticking motion, damping friction in structural dynamics and sliding resistance. The friction coefficients of particles against each other depends on many factors (a set of physical and mechanical properties of particles, chemical and fractional composition, the presence of a lubricant, oxide films, moisture and other conditions, such as volume, angle and height of falling particles), each of which separately difficult to count. The experimental determinations of the value of the coefficient of internal friction during pressing are the most reliable; however, such methods are not applicable in the course of analyzing mixtures in the mining and metallurgical industries due to the fact that bulk materials of this type are characterized by gross porosity and are prone to breaking during similar experiments. To obtain reliable results of mathematical and computer simulations, there is a need to evaluate the mechanics of flow of granular materials or bulk solids. There is a shortage of ways to predict these patterns, that require understanding and conducting extensive basic research. At present, several models are used to describe the connected state of materials (soils, sands, granules and powders): soil mechanics, hydromechanical (continuum mechanics), continuity hypothesis (phenomenological model). All existing methods are based on the average value of the characteristics of a large number of particles and can not be used to describe models with high fractional void volume, and as a result, do not describe each discrete particle in the composition of the flow of bulk materials. This article provides an overview of existing methods for assessing the dynamic friction of solids, their applicability in various situations, as well as the development trends of this scientific field.

1. Introduction

Bulk materials are common in the mining and metallurgical industries [1]. This is due to both the ease of transportation and the possibility of minimizing the energy required for the implementation of the main physical and chemical transformations, as well as the completeness of the process.

A number of industrial wastes from the metallurgical and mining industries are characterized by a dusty form, including carbonaceous feed ashes used as fuel [2]; dust carried away from technological units due to the turbulent mode of air movement [3] and others.

The applicability of bulk materials is determined by a number of parameters, which include both the average geometric (shape, size) and physical characteristics. Depending on the process, requirements for bulk materials vary. In the case of enrichment, the weight of the particles, as well as their fractional composition, depends on the technological process [4]. At the same time, metallurgical aggregates are
largely characterized by the influence of physical parameters, including the angle of slope, adhesion and humidity, as well as dynamic and static friction [5].

The absence of standardized methods for determining a number of rheological and tribological properties with respect to the charge significantly affects the process of controlling the aggregates. In the case of high-temperature processes, there is no mathematical base, which allows unambiguously describing the technological process with sufficient accuracy, so the furnaces are taken as a “black box”, the control of which requires the introduction of various indirect methods [6-8].

The use of mathematical modeling often describes the aggregate taking into account a number of limitations, which include the applicability of data to similar equipment and consideration of physical and chemical parameters for the average composition of ores, in course of that there are difficulties with scaling and transferring the results. The accuracy of the results of mathematical models depends on the parameters of the incoming ore, as a result of which the model error varies considerably [9-11].

The widespread introduction of computer simulation does not allow solving the problem associated with the optimization of control systems [12-14]. This is due to the significant influence of computer simulation parameters on the accuracy of the resulting model; the lack of methods for determining a number of parameters of bulk media that are applicable, taking into account the characteristics of the charge and ores; the complexity of technological processes and the corresponding significant increase in modeling time; limitations associated with the use of modeling techniques regarding the number of particles considered; possible flaws in the program code, which can lead to inadequate behavior of the material in a given geometry [15, 16].

A number of technological processes involves the use of joint modeling techniques, which greatly affects the modeling time and the complexity of implementing the model as a whole [17, 18]. The above limits the number of simulation iterations, as a result of which the parameters of bulk media are chosen as maximally averaged.

In the case of dynamic friction, there are problems associated with the estimation of this parameter for bulk solids on a laboratory scale. This is caused by the breaking of particles in the course of the experiment, which greatly affects the resulting values. At the same time, during the process it is possible to harden the particles under the influence of high temperatures, which makes it difficult to estimate this parameter under laboratory conditions [19-22].

Dynamic friction is one of the parameters that allow describing the behavior of granular media in drum aggregates, including the tubular rotary kilns, pelletizing drums and ball drums. Supply of bulk materials can also be complicated by the occurrence of stagnant zones and the wear and tear of various movable parts of feeder structures and bins. To be able to implement preventive measures, it is necessary to develop methods that allow in situ determining the parameters of bulk materials, including dynamic friction, which will allow controlling the process equipment, taking into account the characteristics of the ores and charges [23].

This article discusses experimental and computational methods for determining the dynamic friction of bulk materials, as well as the main trends in changing the methods for evaluating these parameters, taking into account the current development of industry.

2. Methods for determining internal and external dynamic friction

External dynamic friction (or dynamic friction between the particle and the wall) is determined by the forces of friction against the walls of the body frames with granules of particles (bucket, bunker, collector, mixer, machine tools). Existing methods for determining external dynamic friction are generally similar to methods for measuring static friction between a particle and a wall, however there are a number of differences, characterized primarily by the mathematical apparatus used to estimate this coefficient.

The definition of tribological parameters on an inclined surface (Figure 1) is characterized by the study of a single particle, which is applicable to processes where the characteristics of the feed bulk material vary within insignificant limits.
Figure 1. Installation for determining rolling friction, where 1 – mount pillar, 2 – plane surface, 3 – protractor group, 4 – cursor, 5 - plummet, 6 – handle, 7 – worm gear drive [24]

The experimental procedure is characterized by fixing the angle of inclination of the plane $\beta$ and the time of passage of the section with the slip $t$. External dynamic friction $\delta$ is determined by the following formula (1):

$$\delta = (\tan \beta - \frac{2.8 L}{g t^2 \cos \beta}),$$

where $L$ – particle path length, that is determined by the following formula $L = 0.5 \cdot g \cdot t^2$ [25].

There are methods to evaluate the bulk material as a collection of particles. Figure 2 presents a method based on the analysis of the phases of free fall of particles and the distribution of components along the height of the flow. The measurement technique when using this unit comes down to the following: initially, the cells are filled for a certain time in the steady-state flow mode by increasing the effective friction coefficient, after which the material distribution density function is determined. The dynamics of the flow of granular material will vary, depending on the change in the angle of inclination of the slope.

Figure 2. Experimental installation consisting of an inclined channel (1), a guide plate (2), a rectangular section and a cuvette (3) divided by partitions (4) into cells [26]

The dynamic coefficient of friction, as a function of normal pressure, is determined by the ratio of shear $\tau$ and normal stress $\sigma$. In this case, the model is based on an increase in the thickness of the layer of shear deformations (normal pressure), which leads to an increase in the dynamic coefficient of friction of particles of irregular shape.

The disadvantages of this method are the complexity of the function of the stress tensor (particle concentration), the determination of the nature of the flow as viscous (dependent on velocity) and the
assumption of stability of the solid phase concentration along the height of the stream. Also, the model does not take into account the energy dissipation in the interaction of particles. Alternatively, it is possible to use the measuring device shown in Figure 3. The bulk material is placed in a rotating chute 8-10 cm from the axis of rotation. By lifting this trough by pulling the fishing line, the particles begin to slip, after which the action of tension ends [27].

Figure 3. Measuring device of external friction, consisting of a frame (1), a rotating chute (2) and fishing line (3) [27] Using this technique, the angle of external friction is calculated by the formula (2):

\[
\sin \alpha_w = \frac{h_x}{l_x}
\]

where \(\alpha_w\) - external friction angle (°), \(h_x\) – height of the raised rotary chute, \(l_x\) - rotary chute length.

There are methods for assessing jointly external and internal dynamic friction (Figure 4). At the same time, internal friction between particles, caused by the resistance to shear of these particles and directed oppositely to the shearing force, characterizes the boundary of the moving and stationary state of the bulk material (particle-particle contact).

Figure 4. The device for determining the frictional characteristics of bulk materials, comprising a housing (1), a vertical shaft drive (2), a bowl (3), a fixed block (4), a contact plane (5), a tractive effort load meter (6), fixed partitions (7), holes in the bowl (8), ring stage (9), samples of the studied materials (10, 11) [28]

The change in material properties (also, a mixture of materials can be used) occurs under the effect of compression by the loading mechanism. After loading the bowl and the fixed block of the studied samples of materials, the shear force is measured and the coefficient of friction is calculated. This experimental technology allows obtaining the results of internal and external friction of rest and movement, as well as coefficients of mutual friction of rest and movement of various granular materials.
depending on the measurement of their shift relative to each other and relatively inflexible materials. The disadvantage of the measurements is the possible reduction in the accuracy of the shear force measurements due to a change in the characteristics of electrical components [29-30], the complexity of the design (centering the bowl and the fixed block, the displacement of samples).

3. Methods for calibrating dynamic friction of bulk materials for further use in DEM modeling

Currently, the main trend in assessing the behavior of bulk materials is the use of DEM-modeling methods [31]. To determine the parameters of bulk materials, integrated methods are used, characterized by the presence of vision systems and neural networks. The experiment is carried out on physical stands, and the behavior of the particles is recorded using WEB cameras. The obtained images are analyzed using vision systems (in the case of direct measurement of the parameter) or are predicted using neural networks [32].

In general, a number of methods can be distinguished that allow estimating the dynamic friction of particle-particle and particle-wall. The shear methods for estimating the coefficients of dynamic friction of bulk materials (Figure 5) are similar to those presented above, including from the point of view of the mathematical apparatus.

![Figure 5](image_url)

**Figure 5.** Triaxial specimen for testing, (a) before triaxial compression and (b) after triaxial compression [33]

The methods that are most widely used make it possible to estimate the parameters by the natural angle of slope, when particles are poured out of bunker-like structures, and one or several side walls are pulled out (Figure 6) [34]. These methods are applicable to charges, which is caused by the similarity of methods with technological processes (including the supply of charge to technological units), as well as the exclusion of the human factor in the analysis of parameters.

Currently, the main trend in the development of methods for calibrating DEM parameters is to refine both single parameters using integrated stands and to develop methods for the aggregate determination of the main physical characteristics of bulk materials [35]. These methods, as well as improving the accuracy of computer models, make it possible to clarify the nature of the behavior of the charge in technological processes and to evaluate the effect of varying parameters, excluding the human factor.
4. Conclusion
1. At present, there are two principal approaches to the measurement of dynamic friction: by the natural angle of the slope and using shear methods. These methods can be implemented both within the framework of traditional methods and using automated systems that are applicable for determining the parameters of DEM-modeling.

2. Traditional methods of measuring internal and external dynamic friction are characterized by a significant influence of external factors on the accuracy of the data obtained, which is conditioned both from the point of view of the design of experimental stands (the presence of movable parts with corresponding wear and etc.) and due to the presence of human participation during the experiment.

3. The development of methods for calibrating the parameters of DEM-modeling allows simplifying the existing approaches, as well as to improve the accuracy of the measured data by automating the measurement systems using vision systems, neural networks and automatic control tools.

4. It seems appropriate to use the methods of parameter calibration both in the framework of DEM-modeling and in the quality control of the charge supplied to process units in the mining and metallurgical industries.

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