Study of energy consumption when mixing bulk materials in a centrifugal-blade mixer

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Abstract. The results of a study of the flowability of finely divided dry materials and mixtures depending on the diameter of the particles and their density are presented, the influence of the mechanical effect and the physicomechanical properties of the materials on the flowability are determined. A mathematical model is constructed that allows one to functionally evaluate the dependence of flowability on the physicomechanical characteristics of the material under study by the method of multiple regression analysis. Polynomial equations are obtained that describe the influence of the flow area, physical and mechanical properties on the flowability of various materials and mixtures. A flowability criterion is proposed that describes the motion of various materials under the action of inertia forces. Partial and universal criteria equations are obtained that describe the energy expenditures for mixing bulk materials.

1. Introduction
The effectiveness of technological processes is an important task of scientific and technological progress [5]. First of all, efficiency is determined by energy costs, which occupy the first positions in the cost of production. The energy needs in electricity of mankind are increasing year by year. Its effective use can sometimes be dictated simply by a shortage of power of electric transformers or quotas. Thus, the solution of the problems of rational implementation of technological processes is a search for a compromise between the time and energy costs.

2. The purpose of the study
In this paper, we consider the problems of rational energy expenditure when mixing bulk materials.

3. The object of the study
The object of the study was a centrifugal-blade mixer of powdered and granular materials. The subject of the study was the physical and mechanical characteristics of bulk materials, as well as operational and structural parameters of the mixer.

4. Materials and methods
A well-known technique for calculating the mixing power during the process in liquid and gas environments [3,4] consists in solving the criterion equation that relates, in the general case, the criteria for hydrodynamic similarity (Reynolds, Euler, Froude) and geometric equipment simplexes. Mixing bulk media are complicated by the fact that it is impossible to calculate the Reynolds criterion for them due to the absence of such characteristic as viscosity (μ, Pa · s or ν, m² / s). In principle,
dispersed material as a continuous medium can be characterized by the concept of “flowability”. According to OFS.1.4.2.0016.15 “The degree of flowability of powders” is a complex technological characteristic determined by the dispersion and shape of particles, residual moisture and particle size distribution of the powder system. Flowability is defined as the time during which a certain mass of a substance passes (flows) through an opening of a certain size and is expressed in seconds, related to 100g of the sample, indicating the type of equipment used, nozzle number. Thus, the flowability dimension of dispersed materials does not correspond to the viscosity coefficient for liquid media. In addition, powdery materials and, in rare cases, granular ones are usually characterized by flowability. Therefore, it is not a universal characteristic for a wide range of bulk materials.

5. Discussion of the results
It should be noted that in [1,2] an attempt was made to relate the intensity and efficiency of mixing in a granular medium. The authors of this work proposed a dimensionless characteristic of the flowability of a material, taking into account not only its properties but also the characteristics of the equipment in which the material is processed:

\[ Si = \frac{Q}{\rho \cdot d_k \cdot n} \]  

where \( Q \) – the mass of material precipitating from the cone funnel per unit of time through the hole, referred to the hole cross-sectional area (flowability), kg / (s \cdot m^2); \( \rho \) is the bulk density of the material, kg / m^3; \( d_k \) - diameter of the conical rotor of the mixer, m; \( n \) – rotor speed, s^{-1}.

In this work, several equations of the form \( K_N = C \cdot S_i^m \) are presented. It should be noted that the coefficient "C" and the indicator of degree "m" for different materials, even similar in their properties, differ significantly, which limits the application of the results.

We propose to use a similar approach, but replace the value of Si with another parameter. Considering the mixing of bulk materials in centrifugal vane mixers, which are simple in design and are used for a wide range of bulk materials, it is proposed to consider the following factors. The characteristics of the mixer are the diameter of the mixer \( D \), m and its rotation frequency \( n \), s^{-1}. The key characteristics of the material were selected - bulk density \( \rho \), kg / m^3; the coefficient of internal friction \( k \) and the mass-average particle size \( d \), m. Using these characteristics, it is proposed to operate with two dimensionless complexes of physical quantities. This is a common power criterion characterizing the efficiency of energy consumption:

\[ K_N = \frac{N}{\rho \cdot n^3 \cdot D^5} \]  

as well as a criterion characterizing the intensity of mixing of the granular mass:

\[ S = \frac{(n \cdot D)^2}{g \cdot k \cdot d} \]  

where \( N \) is the power consumed by mixing, W; \( g \) is the acceleration of gravity, m / s^2. Criterion S is a measure of the ratio of inertia forces and forces of resistance to mixing.

In the course of experimental studies, we used the simplest version of a centrifugal-blade mixer. We are talking about a cylindrical apparatus with a flat bottom and an agitator in the form of two flat radial blades having an inclination to the plane of the bottom of the apparatus. At the first stage, we conducted preliminary studies aimed at determining the rational level of filling of the mixing chamber and the angle of inclination of the blades to the bottom plane. The first of these parameters was estimated by us theoretically. Observing the distribution of material over the mixing chamber during mixing, it was found that it focuses on the periphery (Figure 1).
This, obviously, is due to the effect of centrifugal inertia on material particles. Losing their speed after contact with the blades, they are forced out by other particles upward and crumble in the direction of the central part of the bottom. Thus, the angle \( \beta \) shown in Figure 1 is approximately equal to the angle of internal friction of the material \( \alpha_{vn} \), which is one of the main characteristics of bulk materials. Obviously, a small amount of material in the mixing chamber will lead to the fact that its central part will be empty. On the contrary, an excessively large amount of material will create a thick and almost motionless layer above the blades, and basically the lower layer will mix. Therefore, in our opinion, it will be rational for the surface of the material to form a cone with stirring with a vertex approximately in the center of the bottom of the mixing chamber. In this case, the volume of material is determined by the formula:

\[
V = \frac{2}{3} \cdot \frac{\pi}{4} \cdot D^2 \cdot \tan(\alpha_{in}) = \frac{1}{3} \cdot \frac{\pi}{4} \cdot D^2 \cdot k_{in},
\]  

(4)

\( k_{in} = \tan(\alpha_{in}) \) – coefficient of internal friction of the material. It follows that the mixing chamber should be filled to the level of:

\[
H = \frac{1}{3} \cdot D \cdot k_{in}.
\]

(5)

For most bulk materials, the coefficient of internal friction is approximately 0.5 - 0.6, therefore, the level of \( H \approx 0.18D \). Practical experiments using different materials have shown that the \( H: D \) ratio should be taken as 1: 8. The angle of inclination of the blades to the bottom plane was determined empirically. It was taken into account that the power expended on mixing the material in the mixing chamber would be as small as possible, as well as the fact that the material would circulate quite intensively. At a previously determined level of material in the mixing chamber and at different speeds of rotation of the blades, it was found that the angle of their inclination to the bottom plane should be approximately 20 - 40 degrees (for various materials). Thus, it is quite possible to take this angle constant and equal to 30\(^\circ\). The second stage of research was aimed at establishing a relationship between the efficiency and intensity of mixing of the granular mass in a centrifugal-blade mixer. These values are characterized by criteria calculated using formulas (2) and (3). During the
In the experiment, the diameter of the stirrer and its rotation frequency were varied, as well as materials with various properties were used. Thus, the criteria $K_N$ and $S$ were calculated in a variety of combinations of quantities that determine their values. Observing the geometric similarity, we used mixers with a diameter of the mixer 330 mm and 160 mm. The rotational speed of the blades varied from 1.5 r / s to 5 r / s. The experiment was carried out using three materials: wet sand (bulk density $\rho \approx 890$ kg / m$^3$; internal friction coefficient $k \approx 0.71$; mass-average particle size $d \approx 0.0012$ m); moist coal chips ($\rho \approx 615$ kg / m$^3$; $k \approx 0.634$; $d \approx 0.0024$ m); moistened granulated sugar ($\rho \approx 550$ kg / m$^3$; $k \approx 0.609$; $d \approx 0.0017$ m). The materials were moistened in order to reduce their mobility while maintaining satisfactory flowability, as well as to reduce dust formation during the experiment. It should be noted that coal crumb was a polydisperse material with a particle size of about 0.05 ... 7.5 mm. Figure 2 presents graphs of the dependence of the $K_N$ criterion on the value of $S$. On all the graphs, approximating dependences of the power type are indicated.

![Graphs](image_url)

**Figure 2.** Dependence graphs of $K_N$ on $S$.

a) - for a mixer with a diameter of 330 mm; b) - for a mixer with a diameter of 160 mm; c) - generalization of data for mixers of different diameters.
6. Conclusion
An analysis of the results suggests that an equation of the form \( K_N = C \cdot S_m \) adequately describes the mixing process in a centrifugal-blade mixer for a wide range of properties of bulk materials and structural-functional characteristics of the mixer. The equation obtained from the generalized data satisfies various options for combining the above factors. This allows us to conclude that the criteria \( S \) and \( K_N \), as well as the nature of the relationship between them, can be applied to other designs of mixers.

References
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