Analysis of separator operating conditions in a technological module with vibration-centrifugal closed-cycle grinding unit for obtaining high-dispersity materials

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Abstract. The demand for up-to-date building materials and components for their production is constantly growing. The purchasing of foreign analogues is often unreasonable and costly, and the domestic products not always meet the high requirements specified for them. In light of this, it is necessary to develop up-to-date knowledge-intensive technologies of producing building materials of various purpose, as well as materials and products of ceramic, varnish-and-paint, glass and other industries, the basis of which is the application of high-dispersive powders. The extensive use of fine-ground and ultrafine-ground materials resulted in designing a wide range of grinders of various types (ball, vibration, planetary, centrifugal, jet grinders etc.). In each certain unit the special conditions for grinding are created, which allows using them for processing materials with various physical and mechanical characteristics. In this work the mathematical model of closed grinding cycle with combined-action air separator is suggested. In this model the integral functions of partition in air separator have been obtained. The calculated and experimental values of the integral functions of partition in air separator have been compared.

Key words. Technological complex, finely-dispersed product, centrifugal grinding-mixing unit, combined-action air separator, closed grinding cycle.

1. Introduction.
One of the most promising trends of improving the technology of fine and ultrafine grinding of materials is designing the energy-saving technologies of the comprehensive processing and recycling of technogenic materials with the use of selective closed-cycle grinding units [1-3].

In this regard, the implementation of stage-by-stage grinding of materials, providing their micro-defect structure at the first stage, i.e. in press-rolling grinder, and the subsequent selective grinding (of heavy-impact, impact-abrasive or abrasive mechanism of action) in vibration-centrifugal grinding units, is of special interest for science and practice. These units can be of open-cycle and closed-cycle types of grinding [4-8].
2. The main part.
For obtaining high-dispersion materials we have carried out scientific and technological research and a number of studies in creating a special process module. The patent-protected design of aggregates: centrifugal grinding-mixing units (CGMU), have been designed, implementing a set of successive dynamic loadings, which contributes to the efficient obtaining of high-dispersed powders, with the possibility of varying their values or type of action (from heavy-impact to abrasive) depending on the grindability of the ground material [14,15].

2.1. Centrifugal grinding-mixing unit.
A distinctive feature of CGMU (fig. 2) is implementing in one production machine the stages of coarse, fine and ultrafine grinding, which is achieved by various motion trajectories of grinding chambers for providing the corresponding working modes of the grinding media: for coarse grinding – intensive impact load; for fine grinding – impact-abrasive action; and for ultrafine grinding – intensive abrasion [16]. The operating principle of the unit is as follows. The source material is fed through the loading spout and the restraint bar to the upper grinding chamber, making vertical reciprocating movement. This results in passing high energy to grinding bodies, which contributes to their intensive impact action on the material [18,10].

The lengthwise movement of material within the grinding chamber is provided by the natural proping-up with the loaded material. As a result the ground material through the restraint bar, which keeps the grinding bodies inside the grinding chamber, passes to the discharge sleeve, and then to the middle grinding chamber, which also contains grinding bodies. In the middle grinding chamber the material, together with grinding bodies, moves by the ellipsoidal trajectory. The material is ground and through the special restraint bar gets to the lower grinding chamber, where the material under the action of grinding bodies and at the circular motion of the chamber undergoes the intensive abrasion. The dispersity of the end product is mostly determined by the abrasive action in the lower grinding chamber [11,12].

2.2. Combined-action air separator.
In order to improve the efficiency of grinding process in CGMU and to expand the technological opportunities of the module we have designed a combined-action air separator-granulator (patent application № 2018102629), which was tested in high-dispersion materials production line [13].

The structure of separator includes two steps. The first step is intended for separating the coarse product, and the second – for separating fine product.

The separator-granulator operates in the following way. The gas-material flow, consisting of the source material and the energy carrier, passes tangentially to the lower blunted cone through the loading spout. Ascending spirally, the largest particles of the mix are pressed by the centrifugal force to the inner surface of blunted cones, and, losing their speed due to the increasing classifier’s section, fall to the grooved channel of the blunted cone and are discharged through the discharge sleeve. The degree of mix classification can be regulated by changing the energy carrier’s pressure. To provide the free flow of particles through the discharge sleeve its tilt angle to the vertical axis should be more than natural slope of the material. The nonobservance of this condition makes the process of self-induced discharge of particles more difficult.

By changing the technological configuration of the bellmouth and slide gates, the aerodynamic characteristics of the unit can be varied (the speed of gas-material flow, hydraulic resistance) [9,12].

3. Theoretical research
The designed units are used in the grinding processing system (GPS) (figure.1), consisting of CGMU and combined-action air separator.

In figure 1 the closed-cycle GPS is shown. The ground material from hopper 5, preliminarily mixing with the return flow from separator 2, is fed to CGMU. In CGMU the material is ground. The ground material is fed with pneumatic conveyor to separator 2, which divides it to the fine product
(finished powder) and coarse product (return product). The end product is separated from gas in the dust-catching system 3, and the return product goes to the entrance of CGMU for regrinding. The grain-size composition \( R_1(\delta) \) and stock flow \( B_1 \) of CGMU product depend on the grain-size composition of the raw material \( R_c(\delta) \) and its stock flow \( B_c \), as well as on the grain-size composition \( R_2(\delta) \) and the stock flow \( B_2 \) of the return product.

**Figure 1.** The scheme of closed grinding cycle: 1 – CGMU, 2 – separator, 3- finished powder catching system, 4 – fan, 5 – hopper, 6 – mixing unit

Let us suppose that the process in GPS is steady-state and \( Q = \text{const} \). Let the mathematical model of transformation of the material grain-size composition in main units of the scheme be also known. Then the mathematical model of the closed grinding cycle consists of the following set of equations [17,19]

\[
R_1(\delta) = F_M \left( R_0(\delta), B_1, Q, P_1 \right) \tag{1}
\]

\[
\varphi_{\delta} = \varphi_{\delta} \left( \delta, B_1, Q, q_i \right) \tag{2}
\]

\[
\varphi = \int_0^1 \varphi_{\delta}(\delta) dR_1 \tag{3}
\]

\[
R_3(\delta) = \frac{1}{\varphi} \int_0^1 \varphi_{\delta}(\delta) dR_1 \tag{4}
\]

\[
R_2(\delta) = \frac{1}{1-\varphi} \int_0^1 (1-\varphi_{\delta}(\delta)) dR_1 \tag{5}
\]
\[ B_3 = B_i \bar{\phi}, \]
\[ B_2 = B_1 [1 - \bar{\phi}] \]
\[ R_M(\delta) = R_c(\delta \bar{\phi}) + R_2(\delta [1 - \bar{\phi}]) \]
\[ B_1 = B_c + B_2, \]
\[ B_c = B_3, \]
\[ \sum \Delta p_i \{B_i, Q\} = H_B(Q) \]

where \( \varphi_{\delta} \) - separator’s partition curve, \( F_M \) — symbolic notation of a certain grinding kinetics equation; \( P_i \) — vector of parameters, controlling the grinding process; \( q_i \) — vector of parameters, controlling the separation process; \( \Delta p \) — pressure loss at various parts of GPS; \( H_B \) - fan head. In this system the equation (1) describes the transformation of grain-size composition in GPS. The equations (2)-(7) describe the alteration of grain-size composition of the material at the partition in the separation. The alteration of grain-size composition at mixing the raw material and return material flows are described by the equations (8)-(10). The equation (11) presents the process of pneumatic conveying of material in GPS.

The function of CGMU separation is presented in figure 2.

![Figure 2. Integral partition curve of CGMU](image)

To describe a separator’s partition curve let us use one-parameter dependence [20]
\[ \varphi_{\delta} \left( \frac{\delta}{\delta_{\varphi}} \right) = 1 + \exp \left( s \left( \frac{\delta}{\delta_{\varphi}} \right)^2 - 1 \right) \]
\[ (12) \]

where \( s \) – free parameter [21-25]. As parameter \( s \) doesn’t exceed 0.12-0.14, the partition curve for \( s=0.12 \) is presented in figure 3.
As it is not possible to get the analytical solution of the problem (1)-(11), combined with condition (12), the given equations were solved by means of successive-approximation method. For the comparison with experimental values the grain-size composition of coarse and fine product after the separator treatment was taken. In figure 4 the integral functions of separation $R_1, R_2, R_3$ are presented.

### Table 1. Grain-size composition of FQRT samples.

| Sieve residue, % | 3    | 2    | 1    | 0.5  | 0.25 | 0.08 |
|------------------|------|------|------|------|------|------|
| 10.2             | 35.1 | 38.9 | 7.1  | 3.6  | 0.6  |
After the experimental research of the production module, the grain-size analysis of the collected samples was carried out, the findings of which are presented in figure 5 and figure 6.

![Figure 5. Grain-size analysis of grit.](image)

![Figure 6. Grain-size analysis of end product.](image)

Comparison of calculated and experimental values of $R_3$ is given in figure 7. The difference between experimental and calculated data is explained by the fact that for calculation not real partition curve, but the theoretical partition curve was taken (12).
5. Conclusions.
The carried-out design-engineering developments of patent-protected aggregates and their tests have allowed designing a technological complex for fine grinding of materials with various physical and mechanical properties. A mathematic model of the closed grinding cycle with combined-action air separator was suggested. Within this model the integral functions of partition in air separator have been obtained. The grain-size compositions of fine-dispersed particles, obtained by means of the designed units, combined in a technological complex for high-disperity materials production, have been researched. The comparative analysis of calculated and experimental values of integral functions of partition in air separator allows making a conclusion about the high enough accuracy degree of the approximate analytical solution.

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