Energy-saving technological complexes and equipment for producing composite materials

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Abstract. Processing of natural and technogenic materials, utilization of industrial waste, production of goods at the first stage are associated with the grinding of materials. Traditional grinders often do not fully perform their functions, while they have high specific energy consumption and large metal consumption. In addition, for the production of composite materials, it is necessary to mix the original components efficiently, which is not always possible in typical mixer designs. The solution of the problems of joint grinding and mixing is considered in this article. In addition, it is necessary to mix the original components efficiently for the production of composite materials, which is not always possible in typical mixer designs. The solution of the problems of co-grinding and mixing is considered in this article.

1. Introduction
One of the most urgent and popular areas for the development of energy saving technologies today is the creation of small-scale technological complexes of the low-tonnage technological complex (LTC) to produce, for example, fine ceramics [1, 2], finely divided chalk of various grades [3], rational utilization of production wastes [4, 5, 6]. This involves solving both environmental issues related to their storage, transportation and processing of them without freezing and dusting, and technology related to the formation of powdered technogenic materials in compacted bodies of a certain geometric shape and size.

Mini-factories created for the production of ceramic and soil silicate bricks can be one of the examples of the implementation of low-tonnage technologies and energy-saving equipment. The main technological functions (grinding and mixing) in these energy-saving complexes are performed by the developed rotor-centrifugal aggregate of complex dynamic action (Fig. 1) [7].

2. Materials and methods
The aggregate provides grinding of clay materials of medium and low strength (σcј≤60 MPa), such as: clay, chalk, lime, calcareous stone, defecate, gypsum, limestone, etc. The aggregate has the ability to regulate the fineness of grinding and can also perform pneumatic-mechanical mixing of dispersed materials. In the described technological lines, the rotary-centrifugal aggregate (RCA) performs effective dry grinding of the materials instead of wet grinding carried out in a conventional ball mill. This eliminates the energy-intensive drying step.

Using the developed design of the RCA provides a thin-ground product ΣR0.08=30% due to the high energy intensity of the unit, due to the application of combined mechanical action on the crushed material. The implementation of the principle of pneumomechanical mixing of various components in the aggregate allows one to expand the technological capabilities of the installation and to reduce specific energy costs. The use of a common drive containing a single electric motor also makes it possible to reduce the total energy consumption in comparison with analogues. The simplicity of the unit design and the interchangeability of its assemblies allow quick replacement of replaceable operating elements and a significant reduction of costs for machine downtime during repair or maintenance.

Design and technological development of the authors are based on complex analytical studies of grinding and mixing of materials in the developed RCA.
3. Analytical studies of processes of material destruction in the grinding block

At the first stage, the processes occurring in the grinding unit of the aggregate were studied and analytically described. The types of mechanical impact realized in the aggregate were considered: the impact destruction of particles of material by beams, the movement of material loading by a helical blade, the cutting of particles in the main grinding zone, the abrasion of particles in the cylindrical part and the annular gap of the RCA.

Impact destruction of particles of material is characterized by the expression:

\[ \nu_{\text{destr}} \geq \frac{\sqrt{\frac{g \cdot V}{E \cdot G (1 - \varepsilon^2)}}}{\frac{G}{g}} \cdot \frac{v_{\text{destr}}^2}{2} (1 - \varepsilon^2) \geq \frac{\sigma^2}{2E} ; \]  

where \( G \) - gravity force of the particle to be destroyed, N; \( g \) - acceleration due to gravity, m/s\(^2\); \( \varepsilon \) - recovery factor; \( v_{\text{destr}} \) - rate of destruction, m/s; \( V \) - volume of the body, m\(^3\); \( E \) - modulus of elasticity of the material, N/m\(^2\); \( \sigma \) - resistance of the particle to failure, N/m\(^2\).

The force required to move the material with a helical blade is determined from the condition:

\[ F_{\text{mov}} \cdot \pi d_e = P \cdot S_1 + f (P_1 + F_{\text{fr}} \cdot \tan \alpha) \cdot \pi d_e ; \]

\[ F_{\text{mov}} = \frac{P \cdot \tan (\alpha + \rho)}{1 - \tan \rho \cdot \tan \alpha} ; \]  

where \( \rho \) - angle of friction between the helical surface and material loading, deg; \( \alpha \) - angle of the helix of the blade line along its average diameter, degrees; \( S_1 \) - the value of the actual movement of the material load per blade turn, m; \( P_1 \) - total force acting on the material layer, N.

In the cutting zone, the following forces act on the particle (Fig. 2): \( F_c \) - centrifugal force; \( F_{\text{cut}} \) - cutting force; \( F_{\text{fr}} \) - frictional force; \( F_{\text{hd}} \) - force moving a layer of material in the groove of the rotor. The actions of these forces are determined by their resultant, the relationship with which is described by the torque equation

\[ M_{\text{rot}} = \sqrt{R_{\text{rot}}^2 (P_{\text{fr}} \cos \alpha - F_{\text{cut}} \cos \alpha)^2 + R_{\text{rot}}^2 P_{\text{fr}}^2} . \]  

![Figure 1. RCA design with integrated dynamic impact.](image-url)
Figure 2. The scheme of forces acting on a particle.

The geometry of the toroidal profile of the shell should be taken into account in the mathematical description of the processes taking place in the mixing chamber of the RCA.

The working channel of the mixing chamber is bounded by a toroidal surface with a radius of the axial line along the circumference of the torus $r_1$ and the radius of the cross section in the meridional plane $r_2$ (Fig. 3).

Figure 3. A scheme of the working channel of the mixing chamber: 1 - blade of the activator wheel, 2 - dividing wall, 3 - feed opening for the disperse components of the mixture, 4 - feed opening for feeding the main crushed material, 5 - discharge opening.

Taking into account the equation of the toroidal surface after some transformations, the relations determining the geometric profile of the blades of the rotating activator wheel have the form:

$$
\phi_i = \frac{2\pi i}{n} + \omega_f t; \quad r_i \leq r < r_{i+1}; \quad 0 \leq z < \sqrt{r_i^2 - (r - r_i)^2} \quad (4)
$$

where $n$ – number of blades of the activator wheel, pcs; $\omega_f$ - angular speed of rotation of the activator wheel, rad/s; $i = 0, 1, 2, 3, \ldots, n$.

In the course of the studies, two main components of the gas-dispersed flow motion were identified: rotational movement in the direction of rotation of the activator wheel around the axis OZ and rotation of the flow in the meridian planes.

A method for calculating the components of airflow velocity is developed. With technological parameters of the mixing chamber of $n = 1200$ min$^{-1}$; $r_1 = 0.3$m; $r_2 = 0.1$m, calculated aerodynamic parameters were obtained: $\omega_1 = 125.6$ rad / s; $\omega_2 = 94.2$ rad / s; $U_\phi = 37.7$ m / s; $U_z = 9.4$ m / s.

The equations of motion of particles of the disperse phase are obtained:

$$
\frac{d(mV)}{dt} = F_a + F_c \quad (5)
$$

where $F_a$ force of aerodynamic interaction, N; $F_c$ - resultant of external (external) forces acting on a particle, N.

The strength of the medium resistance $F_c$ is:
The equation of motion for particles of irregular shape can be represented in the form:

\[ \frac{dV}{dt} = -\frac{dC_n\Re (V - U) + g + F_\mu + F_s}{m}, \]

where \( \tau = \delta \rho_{fr} / 18 \mu \) is the relaxation time, \( \Phi \) - coefficient of the particle shape.

A technique for calculating the energy-strength parameters of the unit has been developed. The performance of the RCA is determined by two components: \( Q_{gr} \) - the productivity of the grinding unit; \( Q_{mix} \) - productivity of the mixing chamber. In view of the design features of the unit, the following condition must be met: \( Q_{gr} \leq Q_{mix} \).

\[ Q_{gr} = l \cdot b \cdot h \cdot z \cdot \rho \cdot n \cdot k_n \cdot k_c \cdot \cos \alpha, \]

where \( l, b, h \) - length, width and height of the grooves of the rotor, \( m \); \( z \) - number of rotor grooves, \( z = 8-12 \) pcs.; \( \rho \) - bulk density of the material to be crushed, \( \text{kg} / \text{m}^3 \); \( n \) - rotor speed, \( \text{min}^{-1} \); \( \alpha \) - angle of inclination of the cutting grooves to the axis of the rotor, \( \alpha = 5-7 \text{degrees} \); \( k_n \) - coefficient of filling the grooves of the rotor with a material, \( k_c \) - coefficient that takes into account the output clearance of the grinding part of the unit.

The capacity of the mixing chamber is characterized by the volume of the gas-dispersed flow being transported per time unit:

\[ Q_{mix} = \mu \cdot S_{st} \cdot U_\varphi \cdot k \cdot z, \]

where \( U_\varphi \) - circumferential velocity of the center of the working surface of the blade, \( \text{m} / \text{s} \); \( S_{st} \) - area of the working surface of the blade, \( \text{m}^2 \); \( \mu \) - weight concentration of the material in the air stream, \( \text{kg} / \text{kg} \); \( k \) - coefficient that takes into account the nature of the motion of the polydisperse phase in the mixing chamber.

For working of RCA, power is expended on: preliminary destruction of the material particles with beams or knives - \( (N_{fr}) \); moving material with a helical blade - \( (N_{hb}) \); cutting of material in each of the rotor cells - \( (N_{cut}) \); friction of the material layer between the working surfaces of the PCA - \( (N_{fr}) \); overcoming the aerodynamic resistance of the medium in the mixing chamber - \( (N_{mix}) \).

In this case, the power consumption of the drive PCA \( N_{tot} \) (W):

\[ N_{tot} = \frac{N_{fr} + N_{hb} + N_{cut} + N_{fr} + N_{fr}}{\eta}, \]

where \( \eta \) - drive efficiency.

We calculate the power consumed by impact:

\[ N_{fr} = \frac{G \cdot \nu_\varphi^2}{2} (1 - e^2) \cdot n \cdot z_p, \]

where \( z_p \) - average number of particles of the material subjected to impact, pcs.

The power spent on moving the material with a helical blade is:

\[ N_{hb} = \left[ P \cdot S_{fr} + f(P + F_{fr}) \cdot \tan \alpha \right] n, \]

The power used to cut the material:

\[ N_{cut} = \sqrt{R_{rot}^2(F_{fr} - P_{fr})^2 + R_{rot}^2 \cdot P_{fr}^2} \cdot 2\pi m; \]

\[ P_{fr} = \sigma \cdot S_{wor} \cdot S_{wor} = l \cdot d_{wor} \cdot z \cdot F_{fr} = P_{fr} \cdot \mu, \]

where \( \sigma \) - ultimate strength of the material when cutting, MPa, \( S_{wor} \) - area of the working surface, \( \text{m}^2 \); \( d_{wor} \) - the average particle diameter of the material, \( \mu \) - coefficient of external friction.

The power expended on abrasion of the material layer between the working surfaces of the RCA, we find by the formula:

\[ F_r = \frac{1}{2} C_n \rho_{fr} (V - U) |V - U|, \]

\[ \frac{dV}{dt} = -\frac{dC_n\Re (V - U) + g + F_\mu + F_s}{m}, \]

where \( \tau = \delta \rho_{fr} / 18 \mu \) is the relaxation time, \( \Phi \) - coefficient of the particle shape.
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\[ P_{\text{dest}} = \sigma \cdot S_{\text{mix}} ; \quad N_{\text{dest}} = N_{\text{dest}} \cdot \mu ; \quad F_P = P_{\text{th}} \cdot \mu, \tag{15} \]

Power consumed by the mixing chamber:

\[ N_{\text{mix}} = Q_a \cdot \Delta P, \tag{16} \]

where \( Q_a \) - capacity of the chamber by air, \( m^3 / h \); \( \Delta P \) - overpressure in the mixing chamber, Pa.

The overpressure in the chamber is determined by the formula:

\[ \Delta P = \xi_{\text{lo}} \frac{\rho_{2\text{ph}} \cdot L^2}{2F_{\text{lo}}} + \xi_{\text{unl}} \frac{\rho_{2\text{ph}} \cdot L^2}{2F_{\text{unl}}} + \xi_{\text{wc}} \frac{\rho_{2\text{ph}} \cdot L^2}{2F_{\text{wc}}} + \lambda_{2\text{ph}} \frac{d_a}{l_{\text{wc}}} \cdot P \cdot L^2, \tag{17} \]

where \( \xi_{\text{lo}}; \xi_{\text{unl}}; \xi_{\text{wc}} \) - coefficients of local resistance of loading, unloading holes and working channel associated with the bending of the two-phase flow, respectively; \( \lambda_{2\text{ph}} \) - coefficient of friction resistance for a two-phase air-mass flow; \( F_{\text{lo}}; F_{\text{unl}}; F_{\text{wc}} \) - the area of the loading, unloading holes and the cross section of the working channel, respectively, \( m^2 \); \( \rho_{2\text{ph}} \) - density of a two-phase flow, \( kg / m^3 \).

Density and the coefficient of frictional resistance for a two-phase air-liquid flow is found by the formula:

\[ \rho_{2\text{ph}} = \frac{\rho_2 \cdot \rho_1 \cdot (1+\mu) \cdot \lambda_{2\text{ph}}}{\rho_2 + \rho_1 \cdot \mu} ; \quad \lambda_{2\text{ph}} = \frac{0.3164}{Re^{0.25}} + 2.11 \cdot 10^{-5} \cdot \frac{1}{Fr^{0.44}} \cdot \frac{\mu^{0.315}}{d_2^{0.25}} \cdot \frac{\rho_2}{\rho_1} \cdot \frac{1}{\rho_1} \cdot \tag{18} \]

4. Conclusion

The theoretical, experimental, and experimental-industrial studies carried out by the authors can be used to improve the technology of production of dry mixtures and paintwork materials, products made of fine ceramics, bricks, highly active plasticizing additives for the production of foam concrete and small-piece thermal insulation materials; with the re-activation of materials that have lost their astringent properties, with the disposal of various man-made materials, as well as in solving a number of other technological problems.

The main requirements for the LTC are [8, 9, 10]: high efficiency of the components and quality of the finished product, low specific energy consumption, compactness and low metal consumption of equipment. The industrial installation of the RCA has the following technical characteristics: capacity \( Q = 1.5 \ t / h \), power consumption \( N = 5250 \ W \), specific energy consumption \( q = 3.5 \ kW \cdot h / t \), rotor speed \( n = 1350 \ min^{-1} \), fineness of grinding \( \Sigma_{400} = 30\% \). Crushed material: clay, chalk, limestone, lime, gypsum, calcareous stone, defecate, etc. The weight without the electric motor is \( m = 850 \ kg \), overall dimensions (lxbxh) = (2500×1500×1500) * 10^{-3} m.

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