Grinders for processing mineral raw materials

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Abstract. The paper substantiates the importance of increasing the crop yield on cultivated areas through improving soil fertility with the use of innovative grinding equipment that enables preparing mineral materials and caked fertilizers. There is a review of advanced engineering solutions that provide the enhancement of grinding process and reduce energy consumption. The paper presents the results of evaluation of power consumption when grinding inorganic material in the mill with indifferent group that confirm the possibility of efficient use of power, which is basically costless, for improving the energy efficiency of grinding.

1. Introduction
Agricultural production is of great importance in the Russian Federation, since it directly influences the national food safety. The most important sectors of agricultural production are animal breeding, production of grain crops, vegetables, sugar beets, oil and other crops, which sets the task of comprehensively increasing yields, reducing costs and bringing this industry to the forefront of the world in their production and increasing exports. [12].

The most priority aim of the country's economic policy is to create conditions for improving production and technological processes in agribusiness that enable solving the crucial task of increasing the yield of cultivated crops depending on the state of the soil. Since the soil is acidified in many regions of Russia, it does not allow to ramp up fully the potential of the agricultural sector. Moreover, the low mechanization of production processes and high rate of manual labor are also significant obstacles. Therefore, the need arises to use relatively cheap, universal, simple in service and maintenance and energy-efficient grinding equipment in operations involved in improving soil fertility and processing finished products, as there are a number of areas where it is necessary to grind large volumes of various materials. For example, one of the promising areas demanding grinding equipment is the processing of natural chalk and dolomite used for deoxidizing soils, caked fertilizers, grinding of natural sapropel, which is valuable for increasing the soil fertility, as well as in primary (rough) grinding of grain crops: wheat, barley, corn, rye and others.

The practical and economically viable solution for the problem of using the most progressive grinding equipment could be the use of vertical mills of dynamic self-grinding with an indifferent structural group of "MKAD" system [3-6].

As it was learned from previous researches in the field of existing types of grinding equipment, grinding machines, particularly the most widely used drum mills, have low energy conversion efficiency, they are cumbrous, have low specific performance and excessive amount of steel for grinding bodies and lining. Therefore, they cannot meet modern requirements in the field of producing energy-efficient grinding machines [7]. Their main technical drawback lies in the fact that when a piece of ground material is destroyed, it is clamped and destroyed by other working bodies of the machine. This principle applies to jaw, cone and roll crushers. Moreover, to crush pieces and particles, it is necessary to apply high forces that exceed compression capacity of the material. This principle of crushing pieces entails the drawbacks of traditional equipment and technologies used in mineral processing industries. These disadvantages include the massiveness of structures placed on solid foundations of reinforced concrete, the quality of comprising multiple stages necessary to
obtain the finished product of the required fractional composition, which leads to the significant increase in energy consumption, increased capital and operating expenditures [8].

2. Main part
In recent years, in both Russia and foreign countries, the situation that has developed in the field of producing highly efficient grinding equipment caused the intensification of works on designing progressive crushing and grinding machines and technologies. One of the progressive directions in the field of grinding materials, which has the prospect of widespread use in various industries, is a crush method based on the interaction of pieces (particles) of material, which is implemented in vertical mills of dynamic self-grinding of system “MAYA” [9, 10].

Figure 1 shows a self-grinding machine for implementing this method. The ingoing material is loaded on the movable rotor 1 until a stationary vertical casing of the machine is completely filled. The weight of the column of material 2 should press the lower layer 3 with 0.05-0.15 MPa. By means of the rotor 1, the lower layer 3 is rotated with peripheral speed of 10÷70 m/s. In this case, the active zone 4 is formed where the actual grinding of the material occurs due to the collision of particles as they move inside the casing along a toroid course.

Under the centrifugal forces, closed vertical circulation takes place in the volume of the loaded ore mass: downwards – along the axis of rotation; upwards – along the outer walls of the rotor and the facility casing.

The initial material is fed into the facility through the upper part of the casing 5. The finished product is removed from the technological process by a transporting agent, for instance, water, which is passed under pressure through the working space and removed together with the grinding products through openings above the free surface of the ore mass.

All types of mills of this system were distinguished by high specific performance, higher degree of size reduction of the initial material during one cycle with timely reduction of the specific energy consumption and steel saving on grinding bodies and lining, as well as by low noise level during operation and construction simplicity [11].

At the same time, the analysis of the structural and constructive design of mills of this system, as well as the experience of their operation under various conditions, shows that they have exhausted the possibility of reducing energy consumption. The reason lies in the fact that the kinetic energy of moving particles, imparted to them from the edges of a rotating rotor, whose angular velocity for the self-grinding regime should not
exceed the certain critical value $\omega_{cr}$, is used as the basis for the destruction of the crushed material. Violation of these conditions leads to the decrease in productivity and increase in energy consumption [12].

In the last 5-7 years, the alternative direction of improving and developing vertical mills of dynamic self-grinding system “MAYA” is the patented design schemes of vertical mills of dynamic self-grinding system “MKAD”. The technical advantage of these mills in comparison with mills “MAYA” is lower energy consumption during grinding of mineral raw materials including the previously mentioned chalk, dolomite, sapropel and others [13].

Table 1 shows the schematic solutions of vertical mills of dynamic self-grinding, the structural schemes of which have indifferent groups, which allow using the potential energy arising from twisting of the shaft of the driving motor when transmitting different power flows to the column of crushed material along the upper and lower branches of the closed circuit by making these branches with a kinematic mismatch relatively to each other [14, 15].

Figure 2 shows a scheme of supplying power flow to the column of crushed material that contributes to the generation of potential energy during deformation (twisting) of the shaft of the driving motor.

![Diagram](Image)

**Figure 2.** Twisting of the ends of the drive motor shaft in the mill with the indifferent group of system “MKAD” when transmitting power flows (moments) of different magnitude along the upper and lower branches of the closed circuit: 1 – electric motor; 2 – flexible connection of the upper branch; 3 – flexible connection of the lower branch; 4 – motor shaft; 5 – the upper end of the shaft; 6 – the lower end of the shaft; 7 – rotor; 8 – drum; 9 – column of material; 10 – active grinding zone; 11, 12 – leading and driven sprockets at the drive of the drum; 13.14 - leading and driven sprockets of the rotor drive.

The magnitude of the potential energy $E_{pot}$ for known values of the shaft diameter of the drive motor $d_{mot}$, its length $l_{mot}$, and the elastic properties of the shaft material $[\varepsilon]$ will depend on the twist angle of the shaft $\Delta\phi_{tw}$, which can be defined as the difference between torque angles of the lower and upper ends relative to the
initial state before applying a torque supplied along the branches of a closed circuit. The difference in torque angles of the ends of the electric motor at any i-th time is determined by the formula

$$\Delta \phi_{twi} = \phi_{lowi} - \phi_{upi}, \text{ rad}$$

(1)

where $\phi_{lowi}$ и $\phi_{upi}$ – torque magnitude of lower and upper ends in the cross section of the drive shaft at the i-th point in time relative to the initial state before transmitting torque, rad.

Power required to twist the shaft of the drive motor $N_{twi}$ can be defined as

$$N_{twi} = \int_0^t M_{twi} \cdot d(t) \cdot \omega, \text{ W}$$

(2)

where $M_{twi}$ – moment arising due to twisting of the shaft as a result of kinematic mismatch of the branches of the closed circuit; $t_i$ – grinding period, s; $\omega_{moti}$ – angular velocity of the motor shaft at the i-th moment of time, 1/s.

The supply of power flows to the column of crushed material for the mill “MKAD” shows that besides motor shaft twisting, there is a simultaneous deformation of the column of material, which leads to different linear velocities of particles under the influence of rotor 2 and drum 3 rotating in the same direction, yet with different angular speed (see Figure 2). Moreover, the linear velocity of particles of the lower part of column 3 will exceed the linear velocity of particles in the upper part of this column, so for the self-grinding regime to occur, it is necessary to comply with the condition, when angular velocity of the rotor exceeds the angular velocity of the drum, i.e., $\omega_{rot} > \omega_{drum}$. The kinematic mismatch of the branches of the closed circuit is ensured by different gear ratios obtained by reinstalling the sprockets 11, 12, 13 and 14 (see Figure 4). The deformation (twisting) of the shaft of drive motor 1 and the formation of potential energy will depend on the value of this deformation, which will be determined by the difference in the twisting of ends of this shaft $\Delta \phi_{tw}$, elastic characteristics of the shaft material, its length and diameter. The occurrence of potential energy when shaft 2 of motor 1 is twisted leads to the fact that each moving particle will interact with the other with a higher force than in mills MAYA, where the power flow to the material column is supplied directly along a single branch through rotor 2 (see Figure 4a). Therefore, the interaction of particles with high contact stress will lead to the intensification of their destruction per unit time and lower energy consumption. In this case, the maximum force action from the side of the elastic forces of the twisted shaft will be determined by intermolecular forces in the crystal lattice of the material of this shaft, which can be many times greater than the forces created when transmitting power flows from the drive motor to the column of crushed material 9 [16].

To measure power in a closed circuit and consumed from the network, a patented measuring complex has been developed, the principle of which is based on measuring power in a closed circuit by the indirect method by measuring the difference in the angles of twisting of the ends of the motor shaft, which is formed as a result of different torques (power flows) transmitted along the closed circuit branches [17].

Figure 3 shows the structure of an experimental facility for measuring the difference in the twist angles of the upper and lower ends of the motor shaft during grinding of the material $\Delta \phi_{twi}$. 


Figure 3. The structure of experimental facility for measuring the difference in twist angles of the ends of the drive motor shaft \( \Delta \varphi_{tw} \): 1 – the upper sensor of angular displacements of the lower end of the shaft; 2 – lower sensor of angular displacements of the lower end of the shaft; 3 – sensor tang; 4 – drive motor shaft; 5 – upper pin; 6 – lower pin; 7, 8 – mounting brackets.

The power required to twist the motor shaft is determined from the expression

\[
N_{twi} = M_{twi} \cdot \omega_{mot} \cdot J
\]  

(3)

where \( M_{twi} \) – instantaneous moment on the shaft of the motor shaft, formed due to the kinematic mismatch of the branches of the closed circuit, N\cdot m; 
\( \omega_{mot} \) – angular speed of the motor shaft, 1/s.

In turn, the torque on the shaft of the drive motor can be defined as

\[
M_{twi} = \frac{\Delta \varphi_{twi} \cdot [\varepsilon] \cdot J_p}{l_{mot}},
\]  

(4)

where \( l_{mot} \) – motor shaft length, m; 
\([\varepsilon]\) – shear modulus of the material of motor shaft, MPa/m; 
\( J_p \) – polar moment of inertia of the motor shaft, m^4

\[
J_p = \frac{d_{av}^4}{32}.
\]  

(5)

where \( d_{av} \) – average shaft diameter of the electric motor, m.

Special program was developed to measure power in the closed circuit of system “MKAD”. This program performs simultaneous measurement of fixed values of the instantaneous speed of upper 5 and lower 6 ends of the shaft 4 of the motor 1, when transmitting different magnitudes of torques along the lower and upper branches of the closed circuit. In this case, the upper 5 and lower 6 ends of the shaft 2 of the motor 1 will make a different number of revolutions for a fixed period of time \( t \). The information on counting direction of the first (lower) 1 and second (upper) 2 angular displacement sensors, number of counted pulses, difference in twist angles of the ends of the motor shaft \( \Delta \varphi \), number of engine revolutions \( n_{mot} \), rotation frequency of the lower and upper end of the shaft (Figure 5) are displayed on the computer 3.

During the same period, the current rate \( I \), and voltage \( U \), are recorded. The recorded measurement results are displayed on the computer screen.
The power measurement in the closed circuit of the mill uses the method of indirect power measurement, based on the calculation of the expression:

$$N_{CC} = M_{twi} \cdot k_{cal} \cdot k_{trans} \cdot \omega_{moti},$$

(6)

where $k_{cal}$ – calibration coefficient linking the true torque $M_{moti}$ and the difference in twist angles of the ends of the motor shaft – $\Delta \phi_{tw}$;

$k_{trans}$ – transition coefficient linking the number of recorded pulses of the angular displacement sensor for $n$ engine revolutions;

$\omega_{i}$ - instantaneous angular velocity of the drive motor shaft at the $i$-th point in time, $1/s$.

$$k_{trans} = \frac{360}{10000} = 0.036 \text{ deg/grad.}$$

where $n_{npuls} = 10000$ – number of pulses recorded by the angular displacement sensor per revolution of the motor shaft.

Instantaneous power consumed from the $N_{netwi}$ is defined as

$$N_{netwi} = I_{netwi} \cdot U_{netwi},$$

(7)

Table 1 shows patented circuit designs of vertical mills of dynamic self-grinding with the indifferent group.

**Table 1.** Schematic solutions of vertical mills of dynamic self-grinding with an indifferent group.

| №  | Name of schematic solution | Layout | Patent number for invention, publication date | Technical advantage | The way to implement energy savings |
|----|-----------------------------|--------|-----------------------------------------------|---------------------|-----------------------------------|
| 1  | Dynamic self-grinder        |        | Patent for invention №2465960. Published on 10.11.2012 bul. №31 | Reduced energy consumption at the same productivity | Due to the phenomenon of “circulation” of power generated in the closed circuit of the kinematic chain because of the kinematic mismatch of its branches |
| 2  | Mill                        |        | Patent for invention №2496581. Published on 27.10.2013 bul. №30 | Reduced energy costs with the same performance and operating costs | Due to the phenomenon of “circulation” of power generated in the closed circuit of the kinematic chain because of the kinematic mismatch and design simplification |
| 3  | Grinder of dynamic material self-grinding |        | Patent for invention №2520008. Published on 20.06.2014 bul. №17 | Reduced energy costs with the same performance and operating costs | Due to the phenomenon of “circulation” of power generated in the closed circuit of the kinematic chain because of the kinematic mismatch and design simplification |
Figure 4 shows the experimental model of a dynamic self-grinding vertical mill of system “MKAD” with the indifferent group, created on the basis of circuit solution №1 (see Table 1), which allowed practically proving the possibility of the efficient use of the so-called "circulating" power for additional force impact on the crushed material, which leads to an intensification of the interaction between pieces and particles and a reduction in energy consumption.

Figure 4. Experimental facility of vertical mill of dynamic self-grinding with the indifferent structural group: 1 – frame; 2 – cross-piece; 3 - central screed; 4 – support; 5 – electric motor; 6 – plate; 7 – rack; 8 – leading sprocket of the drum drive; 9 – leading sprocket of the rotor drive; 10 – drum; 11 – driven sprocket of drum drive; 12 – loading holes; 13 – outlet openings; 14 – prefabricated tank; 15 – gate; 16 – safety clutch; 17 – tension device; 18 - traction chain of the upper branch; 19 – traction chain of the lower branch.

According to the results of measuring capacities in a closed circuit and the power consumed from the network, conducted on the basis of a full-factor experiment [18, 19], figures 5 and 6 show the results of measuring power in a closed circuit of power consumed from the network for two experiments (№ 6 and № 19). These results were obtained on the facility for measuring the difference in twist angles between the lower and upper ends of the drive motor shaft when grinding mineral material, which is similar to natural chalk with an initial fineness of pieces $D_{int}=30$ mm by physical and mechanical properties.
Figure 5. Results of measuring the power in a closed circuit and the power consumed from the network depending on the influencing factors in the study №6 of a full-factor experiment with the parameters: kinematic mismatch of the branches of the closed circuit $I_{km} = 0.32$; backfill height $H_l = 500$ mm; diameter of the outlets in the drum $d_{outl} = 5.0$ mm: 1 – power consumed from the network; 2 – power in the closed circuit.
Figure 6. Results of measuring power in a closed circuit and power consumed from the network depending on the influencing factors in the study №9 of a full-factor experiment with the parameters: kinematic mismatch of the branches of the closed circuit $l_{ka}=0.42$; backfill height $H_l=380$ mm; diameter of outlets in the drum $d_{out}=9.0$ mm: 1 – power consumed from the network; 2 – power in a closed circuit.

The power in the closed circuit $N_{CC}$ and the power consumed from the network $N_{netw}$ of the network for the grinding period $t$ equaling 180 s was calculated using program MATHCAD-14. The calculation showed that the power in the closed circuit of a dynamic self-grinding vertical mill with an indifferent group exceeds power consumed from the network.

This intensifies the interaction of particles with each other and reduces the energy consumption for the same grinding period. The experimental data on energy consumption showed the possibility of the efficient use of the so-called closed circuit power in order to reduce energy consumption during grinding of the material.

3. Conclusions

1. National food safety can be ensured by improving the standards of works on amending land fertility through the use of advanced technologies, modern cross-functional equipment, that can be used for various operations, including the grinding of minerals needed to increase land fertility and productivity.
2. Existing grinding machines manufactured by domestic industry are expensive, unreliable, difficult to operate, while the grinding process itself is energy-intensive, which leads to a higher cost of products and reduces their competitiveness in the domestic market.
3. Vertical mills of dynamic self-grinding system “MAYA” have reached their saturation point, since only kinetic energy of moving particles is used for the destruction of material, which is imparted to particles by edges of the rotating rotor, the angular velocity of which should not exceed the certain critical value for the course of self-grinding.
4. Vertical dynamic self-grinding mills with the indifferent structural group are the new direction of improving vertical dynamic grinding mills. They allow using not only the kinetic energy of moving particles of a rotating
rotor, but also the so-called "circulating" closed circuit energy, which leads to the reduction in energy consumption with the same performance of the facility.

5. The power in a closed circuit of a mill with an indifferent group is experimentally proved to exceed the power consumed from the electric power network, which helps to reduce energy consumption.

6. The created pilot installation of a vertical dynamic self-grinding mill with an indifferent structural group can become one of the main grinding machines, the use of which in agricultural production will help solving many problems of improving technological processes and increase the productivity of the industry.

References

[1] Postanovleniye Pravitel'stva RF ot 14.07. 2012 №717 «O Gosprogramme razvitiya sel'skogo khozyaystva na 2013-2020 gody»

[2] Federal'nyy zakon RF ot 29 dekabrya 2006 g. N 264-FZ «O razvitiu sel'skogo khozyaystva»

[3] Drovnikov A, Ostanovskiy A, Nikitin Ye, Pavlov I, Osipenko L, Agafonov N 2012 Izmel'chitel' dinamicheskogo samoizmel'cheniya (Novocherkassk: Yuzhno-Rossiyskiy gosudarstvennyy tekhnicheskiy universitet) Byul. 31 p 5

[4] Drovnikov A, Osta-novskiy A, Maslov Ye, Burkov N, Romanenko G 2012 Pat. na izobreteniye №2496581 (Novocherkassk: Yuzhno-Rossiyskiy gosudarstvennyy tekhnicheskiy universitet) Byul. 31 p 5

[5] Drovnikov A, Ostanovskiy A 2012 Zhurnal «Inzhenernyy vestnik Dona» 3 pp 5-6

[6] Drovnikov A, Ostanovskiy A 2013 Gornaya promyshlennost' 6 112 pp 98-100

[7] Drovnikov A, Ostanovskiy A 2017 Sistemy mel'nits dinamicheskogo samoizmel'cheniya konturnogo tipa mo-nografiya (Novocherkassk: YURGPU(NPI)) p 183

[8] Khetagurov V, Kamenetskiy Ye, Khetagurov S, Maksimov N, Sobolev S 2009 Pat. na izobreteniye №2376063 (SKGMI (GTU) Byul. 3 p 4

[9] Gegelashvili M, Burlakov I, Basiyev Ch, Kritskaya M 2013 Gornyy informatsionno-analiticheskiy byulleten' MGGU 4 pp 21-222

[10] Drovnikov A, Ostanovskiy A, Burkov N, Maslov Ye 2013 Yubileyny mezhdunarodnyy sbornik nauchnykh trudov, posvyashchenny 40-leitu kafedry «Maschina i oborudovanie bytovogo i zhilishchno-bytovogo naznacheniya» pp 64-68

[11] Gegelashvili M, Kibizov S, Sverdlin G 2012 Gornyy informatsionno-nauchnyy byulleten' 6 pp 338-345

[12] Ostanovskiy A, Drovnikov A, Chirs'kov A 2015 Izvestiya vyssshikh uchebnykh zavedeniy. Severo-Kavkazskiy region 1 pp 90-95

[13] Ostanovskiy A 2018 Izvestiya vyssshikh uchebnykh zavedeniy. Severo-Kavkazskiy region Tekhnicheskiye nauki 1 pp 66-73

[14] Ostanovskiy A, Osipenko L, Drovnikov A, Maslov Ye 2018 Vestnik BGTV im. V.G. Shukhova 9 pp 75–82

[15] Pilyushchenko V, Vikhlevshchuk V, Leperskiy S, Pozhivanov A 2012 Nauchnyye i tekhnologicheskiye osnovy mikrolegirovaniya stali (Moscow: Nauka) p 384

[16] Ostanovskiy A, Drovnikov A, Rybal'chenko N, Rybal'chenko A, Cherkesova E 2018 Pat. na poleznuyu model' №175743 RF Byul. 15

[17] Tkachova I 2009 Metodika resheniya uchebno-professional'nykh issledovatel'skikh zadach pri izuchenii yestestvennonauchnykh distsiplin (na primere kursa obshchevy fiziki): metodicheskiye rekomendatsii dllya studentov tekhnicheskih spe-tsal'nostey (Orsk : Izdatel'stvo OGTI) p 63

[18] Shvaleva A 2012 Moloday uchonyy 3 pp 427-430