UDC 621.926.5:539.215:531.36
DOI: 10.15587/1729-4061.2021.224948

ESTABLISHING THE EFFECT OF A SIMULTANEOUS REDUCTION IN THE FILLING LOAD INSIDE A CHAMBER AND IN THE CONTENT OF THE CRUSHED MATERIAL ON THE ENERGY INTENSITY OF SELF-OSCILLATORY GRINDING IN A TUMBLING MILL

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The effect of a simultaneous change in the degree of filling a chamber with load κ_{br} and in the content of the crushed material κ_{mbgr} on the efficiency of the self-oscillatory grinding process has been estimated.

Using a method of numerical modeling based on the results of experimental visualization of the flow has helped establish an emergent dynamic effect of the sharp increase in the self-oscillatory action of two-faction loading at a joint reduction in κ_{br} and κ_{mbgr}. A significant decrease in the passive quasi-solid loading motion zone has been detected, as well as an increase in the active pulsation zone and a growth of dilatancy. The manifestation of the effect is enhanced by the simultaneous interaction of increasing the scope of self-oscillations and weakening the coherent properties of particles in a loose large fraction under the influence of the particles of fine fraction. A significant decrease in the values of the inertial loading parameters has been established: maximum dilatancy υ_{max}, the relative scale of self-oscillations $\psi_{R\upsilon}$, the maximum share of the active part of κ_{fammax}, and the generalized complex degree of dynamic activation K_a. A 2.65-time growth of υ_{max} was detected, $\psi_{R\upsilon}$ increased by 5 times, κ_{fammax} – by 4.36 times, K_a – by 18.4 times, at a joint decrease in κ_{br} from 0.45 to 0.25, in κ_{mbgr} – from 1 to 0.

The synergistic technological effect of a sharp decrease in the specific energy intensity E_o/E_s has been established, as well as an increase in the relative performance C_o/C_s in the self-oscillatory grinding, due to a significant increase in the dynamic action of loading, which is exacerbated by the joint interaction of reduced κ_{br} and κ_{mbgr}.

The process of the self-oscillatory grinding of cement clinker has been investigated. A 62 % reduction in E_o/E_s and a 125 % increase in C_o/C_s were detected at a joint decrease in κ_{br} from 0.45 to 0.25, in κ_{mbgr} – from 1 to 0.125.

The established effects make it possible to substantiate the parameters for the energy-efficient self-oscillatory process of grinding in tumbling mills with a conventional structure

Keywords: tumbling mill, chamber filling degree, content of crushed material, self-oscillations, energy intensity

Received date 17.12.2020
Accepted date 01.02.2021
Published date 19.02.2021

1. Introduction

Drum-type mills are used in many industries as the basic equipment for the fine grinding of various solid materials. They are characterized by low operating costs and high reliability of performance. The application of tumbling mills makes it possible to achieve high productivity per unit and, at the same time, maintain functionality at the significant wear of working bodies.

However, the issue related to reducing the energy intensity of such equipment remains relevant [1]. The main disadvantage of tumbling mills is the low mechanical utilization efficiency of the process due to the high specific energy consumption predetermined by the friction dissipation in the working area. This is exacerbated by the relatively low intensity of grinding load circulation in the chamber of the rotating drum since a significant part of it is passive and does not participate in grinding. In this case, the process of grinding by impact action, milling, and crushing is implemented during a non-free fall with subsequent shearing of the active part of the load whose specific share is only 30–45 %.

Conventional trends in the development of tumbling mill parameters have essentially exhausted their capabilities and can no more form the basis for a further dramatic increase in the efficiency of grinding. In particular, there is a direction of improvement of the energy indicators of such mills aimed to intensify the circulation of load by driving it into forced oscillatory movement in the chamber. To this end, it is proposed to use activator elevators in the form of various protruding elements at the chamber surface. However, such devices have limited industrial application due to the accelerated abrasive wear.

At the same time, to drive the intra-chamber load into free oscillations, it is advisable to use the excitement of gravitybased pulsations. The self-excitation of such self-oscillations of the chamber load in a permanently rotating drum is predetermined by the loss of stability in the steady movement of the machine assembly of the mill drive [2]. The factors of instability in the assembly movement are the changes in the variable inertial loading parameters, specifically the axial moment of inertia and the moment of resistance to the drum rotation. Failure to comply with the condition for the asymptotic stability of the assembly movement is predetermined by the achievement of extreme negative values of the second derivative from the axial moment of inertia and the first derivative from the moment of resistance for the angular velocity of drum rotation. The self-excitation of self-oscillations activates a fairly large passive part of the load inside a mill, which significantly increases the intensity of interaction between the grinding bodies and crushed material. That makes it possible to apply, for the generation of load pulsations, conventional structural solutions of tumbling mills with a smooth surface of the working chamber without additional low-reliability lifters [3].

However, the significant variability in the self-oscillatory behavior in the rotating chamber, depending on the complex multi-factional poly grain load structure, significantly complicates the establishment of rational conditions for the effective implementation of such a milling process. This structure is quantitatively characterized by both the degree of filling the chamber with grinding bodies κ_{br} [4] and the degree of filling the gaps between these bodies with particles of the crushed material κ_{mbgr} [5].

Given the above, it is a relevant task to forecast the simultaneous impact of κ_{br} and κ_{mbgr} on the dynamic effect of grinding bodies and the technological and energy efficiency of the self-oscillatory grinding process in the tumbling mill.

2. Literature review and problem statement

Study [3] evaluated the dynamic parameters of the impact action of load and the energy and technological parameters of self-oscillatory grinding for one discrete value of the filling degree κ_{br}=0.45 and the content of the material κ_{mbgr}=1. The value and power of impact pulses of load particles were approximated numerically. The ratio of impact pulses for the self-oscillatory and steady motion modes is 2.32–2.39. The ratio of pulse power is 5.41–5.7. It was established that under such conditions, during the self-excitation of self-oscillations, the energy intensity of grinding, decreases, compared to conventional grinding, by 27.2 % while productivity increases by 6.7 %.

Paper [4] considers the effect of changing κ_{br}=0.25–0.45 on the impact effect of loading and the efficiency of self-oscillatory grinding for one discrete value of the material content κ_{mbgr}=1. A significant increase in the values and power of impact pulses with a decrease in κ_{br} was detected. The increase in the pulse value at κ_{br}=0.45 was 2.4 times, at κ_{br}=0.35 – 3.1 times, at κ_{br}=0.25 – 5.8 times. The growth of pulse power at κ_{br}=0.45 was 5.7 times, at κ_{br}=0.35 – 9.6 times, at κ_{br}=0.25 – 45.5 times. An increase in the energy and technological efficiency of the grinding process with a decrease in κ_{br} was established. The decrease in the relative specific energy intensity at κ_{br}=0.45 was 27 %, at κ_{br}=0.35 – 42 %, at κ_{br}=0.25 – 55 %. The increase in the relative performance at κ_{br}=0.45 was 7 %, at κ_{br}=0.35 – 30 %, at κ_{br}=0.25 – 46 %.

The effect of varying κ_{mbgr}=0.125–1 on the modes of movement of grinding bodies and the effectiveness of self-oscillatory grinding for one discrete value κ_{br}=0.45 was studied in [5]. The decrease in such inertial load parameters as maximum dilatancy $\upsilon_{\max}$, the relative scope of self-oscillations $\psi_{R\upsilon}$, the maximum share of the active part of $\kappa_{fam\max}$, and the generalized integrated degree of dynamic activation K_a was detected with the growth of κ_{mbgr}. With an increase of κ_{mbgr} from 0 to 1, the decrease in $\upsilon_{\max}$ was 29 %, $\psi_{R\upsilon}$ – 7 %, $\kappa_{fam\max}$ – by 2.9 times, K_a – 4.2. The decrease in the specific energy capacity of grinding at κ_{mbgr}==1 was 27 %, at κ_{mbgr}=0.5625 – 38 %, at κ_{mbgr}=0.125 – 44 %. The increase in the relative performance at κ_{mbgr}=1 was 7 %, at κ_{mbgr} =0.5625 – 26 %, at κ_{mbgr}=0.125–39 %.

Works [4, 5] showed that with a decrease in the value of one of the factors κ_{br} and κ_{mbgr}, the values of the dynamic and inertial parameters and characteristics of the self-oscillatory motion of load are increased. These parameters include the maximum load dilatancy over one pulsation period $\upsilon_{\max}$, the relative scale of self-oscillations $\psi_{R\upsilon}$, and the maximum mass fraction of the active load part $\kappa_{fam\max}$. In addition, the integrated dynamic characteristic of the self-oscillatory movement is the degree of dynamic activation of load K_a. It was found that such an increase in dynamic action was predetermined by a separate decrease in the share of the passive quasi-solid zone, an increase in the share of the active pulsation zone of movement in the cross-section of the chamber, as well as an increase in the dilatancy and scope of self-oscillations.

Papers [3–5] demonstrated that as the value of one of the factors κ_{br} and κ_{mbgr} decreases, the relative process performance value C_o/C_s increases while the value of the specific energy intensity E_o/E_s decreases. It was found that such a change in the characteristics of the self-oscillatory grinding is predetermined by an increase in the dynamic effect of grinding load on the crushed material due to the influence of a separate factor.

However, the characteristics of grinding processes in tumbling mills depend significantly on both the size of the share of chamber κ_{br}, which is filled with grinding bodies and on the magnitude of the material content in load κ_{mbgr}. At the same time, the effect of the simultaneous variation in κ_{br} and κ_{mbgr} on the modes of movement of grinding bodies was not investigated as an additional factor in papers [3–5].

A series of attempts were made to theoretically and experimentally analyze the individual impact of κ_{br} and κ_{mbgr} on the dynamic, energy, and technological parameters of conventional established processes of dry and wet milling.

Study [6] applied a discrete element method (DEM) and a mechanistic model to numerically assess the impact of κ_{br} on the grinding performance and the specific drive power of the tumbling mill. Three-dimensional numerical DEM modeling of the influence of κ_{br} in a semi-self-grinding (SSG) mill on the impact effect of the grinding load was performed in [7]. In [8], three-dimensional DEM modeling of the impact of κ_{br} on the technological, energy, and operational parameters of SSG mills was carried out.

In [9], the impact of κ_{br} on the productivity and energy intensity of the process of grinding fragile materials in tumbling mills was numerically investigated. It was established that with an increase in κ_{br}, the load's kinetic energy increases while productivity improves. However, a significant increase in κ_{br} causes the dissipation of the energy of grinding bodies due to the increased collision and reduced productivity and energy efficiency of grinding. The linked cell method was used in [10] for two-dimensional numerical simulation of the effect of κ_{br} on the grinding process in a tumbling mill. Reduced milling performance with an increase in κ_{br} was established. In [11], DEM and the linked cell method were used to analytically assess the effect of κ_{br} on grinding in tumbling mills. Increased productivity was detected, with an increase in κ_{br}, due to an increase in the kinetic energy of grinding bodies. However, with a significant increase in κ_{br}, a decrease in the energy efficiency of the process due to the dissipation of energy caused by an increase in the frequency of non-elastic collisions of grinding bodies was established.

An analytical model for predicting the effect of crushed material on the specific rate of dry destruction in a tumbling mill was proposed in [12]. Underlying that model is the concept of energy absorption when the material's particles absorb the kinetic energy of the motion of load inside the chamber.

The authors of [13] applied DEM to simulate the impact of κ_{br} and κ_{mbgr} on the dynamic effect of grinding load during dry grinding in an SSG mill. It was found that with an increase in κ_{br} and a decrease in κ_{mbgr}, the impact effect of fragile destruction decreases, due to dissipation, and the abrasive effect of crushing increases. DEM was employed in [14] to model the effect of κ_{br} and κ_{mbgr} on the dynamic effect of grinding load during dry grinding in an SSG mill. The dissipation of energy at grinding bodies' collision was taken into consideration. It was found that with an increase in κ_{br} and a decrease in κ_{mbgr}, the impact effect of fragile destruction decreases while the abrasive effect increases during crushing. The effect of discrete values of κ_{br}=0.05, 0.1, 0.15, 0.2, 0.25, and 0.3 and κ_{mbgr} on the impact effect of load and the drive power of the mill during the dry grinding of iron ore was numerically, by using DEM, and experimentally studied in [15]. It was established that with an increase in κ_{br}, the drive power increases. At κ_{br}=0.2, the impact forces of ball grinding bodies in the load acquire maximum values. It was shown that with an increase in κ_{mbgr}, the lifting height of the load in the rotating chamber increases, its circulation is activated, and the drive power of the mill increases. In addition, the increase in κ_{mbgr} significantly reduces the impact effect of the load due to the depreciation of the interaction between grinding bodies. The authors of [16] experimentally studied the effect of κ_{br} and κ_{mbgr} on the dynamic parameters of a load inside the chamber of a tumbling mill during the dry and wet grinding of iron ore. The values of κ_{br} were 0.2, 0.3, and 0.4; κ_{mbgr} – 60, 80, and 100 %. An increase in the frequency and energy of the impact action of the load with an increase in κ_{br} was detected. It was established that the smallest specific energy intensity of the dry milling process is achieved at κ_{br}=0.2.

The authors of [17] experimentally studied the effect of κ_{br} and material content on the effectiveness of the platinum ore wet grinding process. The filling was κ_{br}=0.2–0.4, pulp concentration – 50–80 %. The growth of milling fineness with an increase in κ_{br} was established. An increase in the relative process performance with a decrease in material content was detected. The effect of κ_{br} and the material content on the impact effect of grinding load in the wet grinding of copper ore in a tumbling mill was experimentally studied in [18]. The values of κ_{br} were 0.12, 0.18, 0.24, 0.3, and 0.36; the pulp content was 40, 50, 60, and 70 %, the concentration of the pulp was 0,42, 84, 126, 168, and 210 %. A decrease in the impact force of grinding bodies with an increase in κ_{br} was established. It was found that with an increase in the content of the material, the impact action of the load decreases in size and frequency due to damping the interaction between grinding bodies. It was established that the best grinding conditions are implemented at a pulp concentration of 50–60 % and its content of 100 %. Paper [19] proposes an empirical model of the influence of κ_{br} and the content of the crushed material on the pattern of load's motion in the cross-section of the chamber. The model makes it possible to predict the characteristics of wet ore grinding in a tumbling mill over a wide range of parameter changes. The influence of κ_{br} and the material content on the performance of the wet grinding of copper ore and the drive power of the tumbling mill was experimentally studied in [20]. The values of κ_{br} were 0.1–0.3, the pulp content was 50–250 %, the concentration of the pulp was 40–80 %. It was established that the best grinding conditions are implemented at κ_{br}=15–20 %, at the pulp content of 100–150 %, and the pulp concentration of 60–70 %. The authors of [21] experimentally investigated the effect of κ_{br} and material content on the process of the wet grinding of copper ore in a tumbling mill. The values of κ_{br} were 10, 15, 20, and 25 %, the concentration of the pulp was 40, 50, 60, 70, and 80 %, the pulp content was 50–250 %. It was established that the best grinding conditions are implemented at a pulp content of 100–150 %, κ_{br}=20–25 %, and a pulp concentration of 60–70 %. It was found that with an increase in the content of the material, the damping effect increases, which causes a decrease in the impact interaction of grinding bodies and a decrease in grinding performance.

Consequently, the data acquired from analytical and numerical modeling and experiments have revealed a significant impact of a separate change in the degree of filling κ_{br} and the content of the material κ_{mbgr} on the parameters of the grinding process in tumbling mills. Such an impact is to increase the impact action of the grinding load with a decrease in κ_{br}. However, with an increase of κ_{br}, the impact and abrasive action increases, the dissipation of the kinetic energy of grinding bodies increases as a result of collisions, and the energy efficiency of grinding decreases. At the same time, with an increase in κ_{mbgr}, the dynamic action of the load is reduced due to damping the interaction and dissipation of the kinetic energy of the movement of grinding bodies. In addition, with an increase in κ_{mbgr}, the drive power of the mill increases while the relative productivity of grinding decreases. However, such results apply only to the conventional grinding process under a simple steady motion mode of the load inside the chamber.

No models have been built so far to determine the joint impact of κ_{br} and κ_{mbgr} on the dynamic and technological parameters of milling during the self-excitation of the complex transitional pulsation mode of the load movement inside the chamber. This is due to the insurmountable difficulties associated with analytical and numerical modeling and the increased complexity of the hardware experimental study of the behavior of the poly-grained load of the rotating drum chamber during the self-excitation of self-oscillations due to the loss of stability of the system movement. The lack of such models is especially negative in the case of the implementation of an innovative self-oscillatory process of grinding in tumbling mills.

3. The aim and objectives of the study

The aim of this work is to establish the joint impact of the degree of filling the chamber with load and the content of the crushed material in it on the characteristics of the dynamic effect of the pulsation loading and the parameters of the conventional and self-oscillatory grinding in a tumbling mill. That would make it possible to predict the effectiveness of the implementation of the self-oscillatory grinding process while varying the filling extent of the chamber and the content of the crushed material in the load.

To accomplish the aim, the following tasks have been set:

– to determine, based on the comparison, the qualitative nature of the joint impact of the degree of filling the chamber and the content of the small fraction on the value of the dynamic action of the self-oscillatory two-fraction load of the rotating chamber;

– to identify, based on the comparison, the qualitative nature of the joint impact of the degree of filling the chamber and the content of the crushed material in the load on the technological and energy efficiency of the self-oscillatory process of grinding in a tumbling mill.

4. Materials and methods

4. 1. Methodology for determining the effect of the structure of a two-faction self-oscillatory load in a rotating drum on dynamic action

The movement of the load inside the chamber in the form of a transitional self-oscillatory gravitational flow is extremely difficult to study experimentally. The high sensitivity of grainy environment currents to external influences causes significant violations in the complex nature of particle interaction due to the manifestation of local boundary effects. The main difficulties arise due to the increased sensitivity of the grainy flow to the internal hardware sensing. Therefore, the principal method accepted in our experimental study was physical visualization, since the marginal boundary effect of a grainy load at the transparent end wall of the chamber turned out to be insignificant.

It was believed that the length of the rotating drum chamber significantly exceeds the length and thus the influence of the end walls on the movement of the load inside the chamber can be neglected. The two-dimensional flow of the load was considered, in the plane perpendicular to the axis of the chamber. To determine the inertial and dynamic parameters of self-oscillations, we applied a method of numerical modeling based on the results from the experimental visualization of load motion patterns [3–5]. This method's implementation algorithm implies the consistent execution of the following stages:

1) fill the drum chamber with a portion of a two-fractional grainy load with certain values of the degree of filling κ_{br} and the content of the fine fraction κ_{mbgr};

2) achieve the self-excitation of load's self-oscillation at a maximum span when the drum is rotated stationary;

3) video record the transitional self-oscillatory motion of the load in the cross-section of the rotating chamber with a transparent end wall;

4) establish motion patterns in the cross-section of the chamber, corresponding to one period of self-oscillations;

5) highlight flat geometric shapes in the patterns corresponding to the distribution, taking into consideration dilatancy, of the entire load and its active and passive parts;

6) measure the area of the selected shapes;

7) calculate, from corresponding expressions [5], values of the inertial and dynamic parameters of the load for certain values of κ_{br} and κ_{mbgr}.

The modeling method based on the experimental visualization of the flow makes it possible to calculate the following [5]:

1) the maximum dilatancy value during one pulsation period $\upsilon_{\max}=S_{fm\max}/(\kappa_{br}\pi R^2)$;

2) the relative scale of self-oscillations $\psi_{R\upsilon}=[2(S_{fm\max}-S_{fm\min})]/(S_{fm\max}+S_{fm\min})$;

3) the maximum mass fraction of the active part of the load $\kappa_{fam\max}=1-S_{fpm\min}/(\kappa_{br}\pi R^2)$;

4) the degree of dynamic activation $K_a=\upsilon_{\max}(1+\psi_{R\upsilon})\times\kappa_{fam\max}$;

($S_{fm\max}$ and $S_{fpm\min}$ – the maximum and minimum value of the area of the geometric shape of the load in the pattern of movement in the cross-section of the chamber over one period; $S_{fpm\min}$ – the minimum value of the area of the geometric shape of the passive fixed part of the load in the pattern of movement in the cross-section of the chamber when reaching the maximum value of dilatancy $\upsilon_{\max}$: R – the radius of the drum chamber).

The degree of dynamic activation K_a is the product of three multipliers. The multiplier $\upsilon_{\max}$ characterizes the maximum dynamic action over one period of self-oscillations, $(1+\psi_{R\upsilon})$ – the range of change in this action over the oscillation period, $\kappa_{fam\max}$ – the maximum mass fraction of the load that performs such an action.

A large fraction of the two-fraction load was modeled by the spherical particles of loose grainy material $\psi_{db}=0.0104$ [3–5]. Small fractions were the Portland cement particles $\psi_{dm}\approx 0.13\cdot 10^{-3}$. Discrete values of the volumetric degree of filling the chamber with a large fraction at rest were $\kappa_{br}=0.25$, 0.35, and 0.45 [4]. The values of the volumetric degree of filling the gaps between spherical bodies at rest with small particles were $\kappa_{mbgr}=0$, 0.25, 0.5, and 1 [5].

To acquire the patterns of the movement of the load in the cross-section of the chamber at the maximum scale of self-oscillations, video recording with a frequency of 24 frames per second was used.

4. 2. Procedure for determining the effect of filling the chamber and the content of the crushed material on the characteristics of grinding

The joint impact of the degree of filling the chamber and the content of the crushed material in the load inside the chamber on the efficiency of the self-oscillation process of grinding in the tumbling mill was assessed for the case of grinding the cement clinker [3–5].

The values of the filling degree of the chamber were $\kappa_{br}=0.25$, 0.35, and 0.45. The values of the content of the crushed material were $\kappa_{mbgr}=0.125$, 0.5625, and 1.

The technological efficiency of the self-oscillatory grinding process was evaluated according to the relative productivity C_o/C_s, energy efficiency – according to the relative specific energy intensity E_o/E_s [5].

According to the obtained experimental data, the technological parameters of grinding processes in the tumbling mill at the degree of filling the chamber of $\kappa_{br}=0.25$ accept the following values: $C_o=0.374$ and $C_s=0.156$ at $\kappa_{mbgr}=0.125$, $C_o=0.653$ and $C_s=0.357$ at $\kappa_{mbgr}=0.5625$. At the same time, the relative energy intensity of the self-oscillatory process is $P_{do}/P_{ds}=0.665$ ($\psi_{\omega o}=1.05$) [4].

Then the relative performance and specific energy intensity of the self-oscillation grinding process at $\kappa_{br}=0.25$ accept the following values: $C_o/C_s=2.4$ and $E_o/E_s=0.277$ at $\kappa_{mbgr}=0.125$, $C_o/C_s=1.83$ and $E_o/E_s=0.364$ at $\kappa_{mbgr}=0.5625$. The process characteristics at $\kappa_{br}=0.25$ and $\kappa_{mbgr}=1$ were defined in [4]: $C_o/C_s=1.46$ and $E_o/E_s=0.455$.

The parameters of grinding processes in the tumbling mill at the degree of filling the chamber of $\kappa_{br}=0.35$ accept the following values: $C_o=0.77$ and $C_s=0.453$ at $\kappa_{mbgr}=0.125$, $C_o=0.71$ and $C_s=0.467$ at $\kappa_{mbgr}=0.5625$. The relative energy of the self-oscillatory process is $P_{do}/P_{ds}=0.749$ ($\psi_{\omega o}=1.075$) [4].

The relative characteristics of the self-oscillatory grinding process at $\kappa_{br}=0.35$ accept the following values: $C_o/C_s=$

$=1.7$ and $E_o/E_s=0.44$ at $\kappa_{mbgr}=0.125$, $C_o/C_s=1.52$ and $E_o/E_s=$ $=0.492$ at $\kappa_{mbgr}=0.5625$. The process characteristics at $\kappa_{br}=0.35$ and $\kappa_{mbgr}=1$ were defined in [4]: $C_o/C_s=1.3$ and $E_o/E_s=0.576$.

The process characteristics at $\kappa_{br}=0.45$ were defined in [3] and [5] ($\psi_{\omega o}=1.1$): $C_o/C_s=1.39$ and $E_o/E_s=0.558$ at $\kappa_{mbgr}=0.125$ [5], $C_o/C_s=1.26$ and $E_o/E_s=0.617$ at $\kappa_{mbgr}=$ $=0.5625$ [5], $C_o/C_s=1.067$ and $E_o/E_s=0.728$ at $\kappa_{mbgr}=1$ [3].

5. The study results

5. 1. Results of determining the joint impact of a two-faction load's structure on dynamic action

Sequential motion patterns for one period of self-oscillations for $\kappa_{br}=0.25$ at $\kappa_{mbgr}=0$ are shown in Fig. 1, at $\kappa_{mbgr}=0.25$ – in Fig. 2, at $\kappa_{mbgr}=0.5$ – in Fig. 3, at $\kappa_{mbgr}=1$ – in Fig. 4.

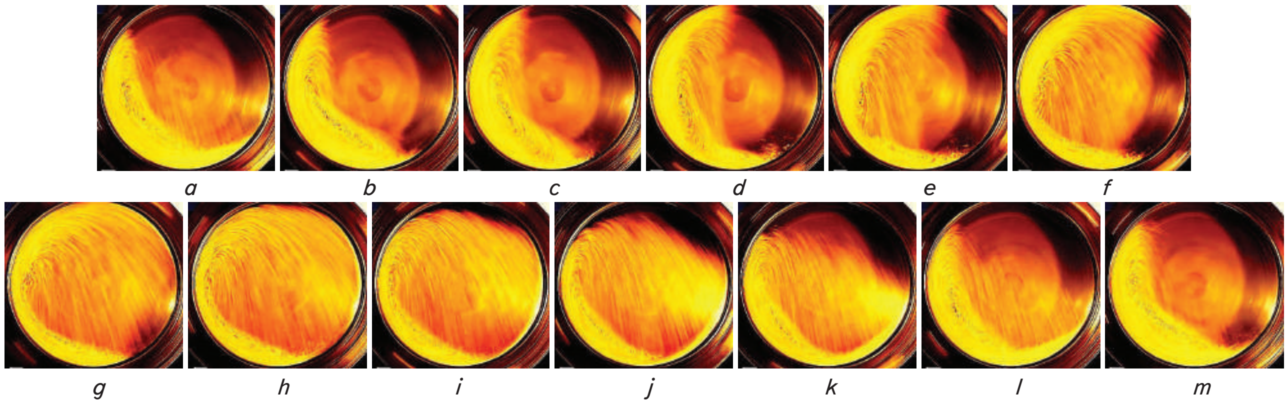


Fig. 1. Sequential load motion patterns over time t for one period of self-oscillations T_{op} at maximum scope at the relative particle size of the large fraction in the chamber of the rotating drum $\psi_{db}=0.0104$, the degree of filling the chamber with particles of a large fraction of the load at rest $\kappa_{br}=0.25$, the degree of filling the gaps between the particles of the large fraction with the particles of the fine fraction of the load at rest $\kappa_{mbgr}=0$, and the relative speed of rotation of the chamber $\psi_{\omega}\approx 1$: *a* – $t=0$; *b* – $t=T_{op}/12$; *c* – $t=2T_{op}/12$; *d* – $t=3T_{op}/12$; *e* – $t=4T_{op}/12$; *f* – $t=5T_{op}/12$; *g* – $t=6T_{op}/12$; *h* – $t=7T_{op}/12$; *i* – $t=8T_{op}/12$; *j* – $t=9T_{op}/12$; *k* – $t=10T_{op}/12$; *l* – $t=11T_{op}/12$; *m* – $t=T_{op}$

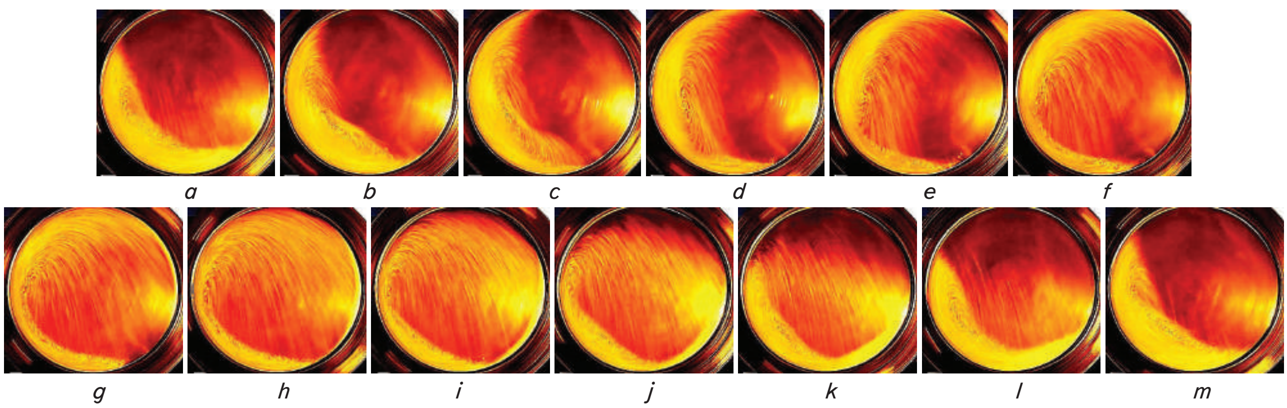


Fig. 2. Sequential load motion patterns over time t for one period of self-oscillations T_{op} at maximum scope at $\psi_{db}=0.0104$, the average relative particle size of small fraction in the chamber $\psi_{dm}\approx 0.13\cdot 10^{-3}$, $\kappa_{br}=0.25$, $\kappa_{mbgr}=0.25$, and $\psi_{\omega}\approx 1$: *a* – $t=0$; *b* – $t=T_{op}/12$; *c* – $t=2T_{op}/12$; *d* – $t=3T_{op}/12$; *e* – $t=4T_{op}/12$; *f* – $t=5T_{op}/12$; *g* – $t=6T_{op}/12$; *i* – $t=7T_{op}/12$; *h* – $t=8T_{op}/12$; *j* – $t=9T_{op}/12$; *k* – $t=10T_{op}/12$; *k* – $t=11T_{op}/12$; *m* – $t=T_{op}$

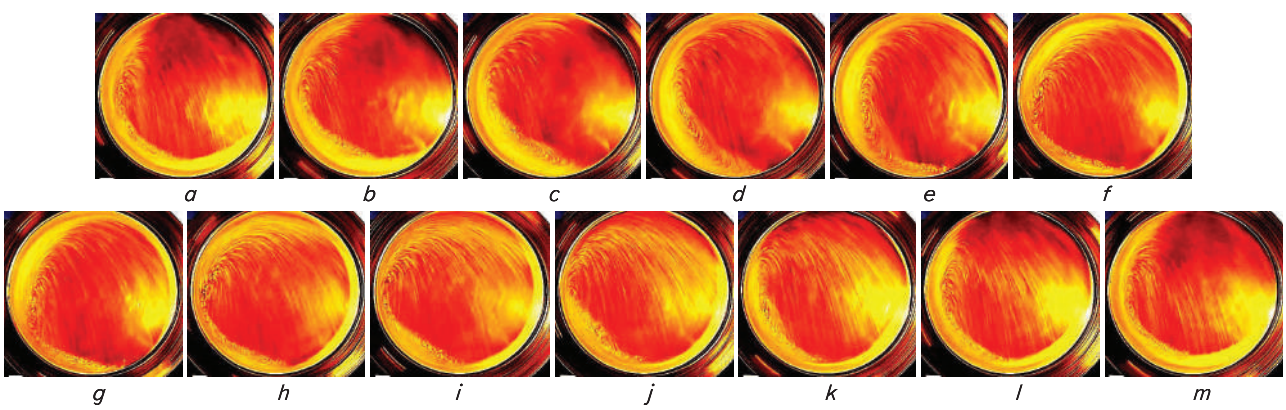


Fig. 3. Sequential load motion patterns over time t for one period of self-oscillations T_{op} at maximum scope at $\psi_{db}=0.0104$, $\psi_{dm}\approx 0.13\cdot 10^{-3}$, $\kappa_{br}=0.25$, $\kappa_{mbgr}=0.5$, and $\psi_{\omega}\approx 1$: *a* – $t=0$; *b* – $t=T_{op}/12$; *c* – $t=2T_{op}/12$; *d* – $t=3T_{op}/12$; *e* – $t=4T_{op}/12$; *f* – $t=5T_{op}/12$; *g* – $t=6T_{op}/12$; *h* – $t=7T_{op}/12$; *i* – $t=8T_{op}/12$; *j* – $t=9T_{op}/12$; *k* – $t=10T_{op}/12$; *l* – $t=11T_{op}/12$; *m* – $t=T_{op}$

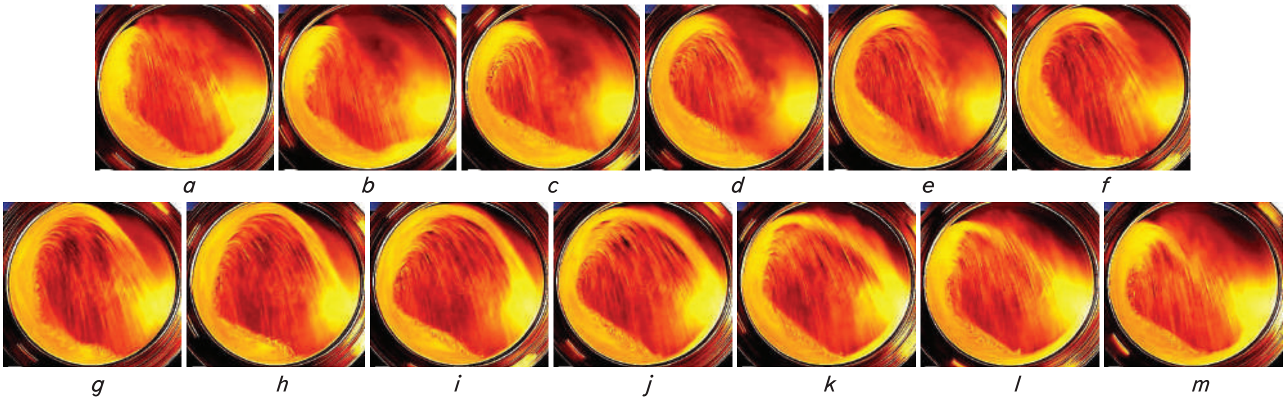


Fig. 4. Sequential load motion patterns over time t for one period of self-oscillations T_{op} at maximum scope at ψ_{db}=0.0104, $\psi_{dm}\approx 0.13\cdot 10^{-3}$, κ_{br}=0.25, κ_{mbgr}=1, and $\psi_{\omega}\approx 1$: a – t=0; b – $t=T_{op}/12$; c – $t=2T_{op}/12$; d – $t=3T_{op}/12$; e – $t=4T_{op}/12$; f – $t=5T_{op}/12$; g – $t=6T_{op}/12$; h – $t=7T_{op}/12$; i – $t=8T_{op}/12$; j – $t=9T_{op}/12$; k – $t=10T_{op}/12$; l – $t=11T_{op}/12$; m – $t=T_{op}$

Sequential motion patterns for one period of self-oscillations at κ_{br}=0.35 at κ_{mbgr}=0 are shown in Fig. 5, at κ_{mbgr}=0.25 – in Fig. 6, at κ_{mbgr}=0.5 – in Fig. 7, at κ_{mbgr}=1 – in Fig. 8.

The charts of the obtained results from experimental determining of the change in parameters on the degree of filling the chamber and the content of the small fraction in the load inside the chamber are shown in Fig. 9–16. The values for the parameters at κ_{br}=0.45 were found in [5]. The dependence of change in $\upsilon_{\max}$ on κ_{br} is shown in Fig. 9, $\upsilon_{\max}$ on κ_{mbgr} – in Fig. 10, $\psi_{R\upsilon}$ on κ_{br} – in Fig. 11, $\psi_{R\upsilon}$ on κ_{mbgr} – in Fig. 12, $\kappa_{fam\max}$ on κ_{br} – in Fig. 13, $\kappa_{fam\max}$ on κ_{mbgr} – in Fig. 14, K_a on κ_{br} – in Fig. 15, K_a on κ_{mbgr} – in Fig. 16.

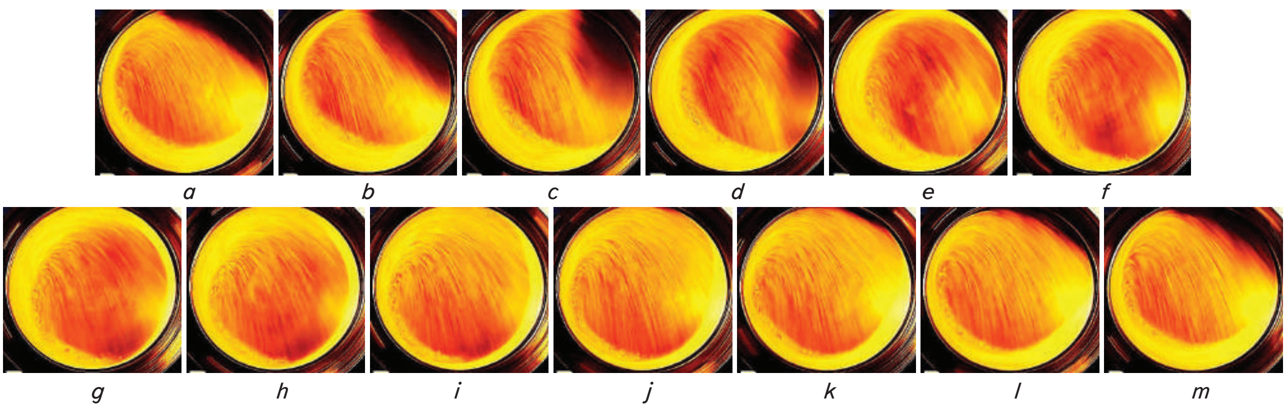


Fig. 5. Sequential load motion patterns over time t for one period of self-oscillations T_{op} at maximum scope at ψ_{db}=0.0104, $\psi_{dm}\approx 0.13\cdot 10^{-3}$, κ_{br}=0.35, κ_{mbgr}=0, and $\psi_{\omega}\approx 1$: a – t=0; b – $t=T_{op}/12$; c – $t=2T_{op}/12$; d – $t=3T_{op}/12$; e – $t=4T_{op}/12$; f – $t=5T_{op}/12$; g – $t=6T_{op}/12$; h – $t=7T_{op}/12$; i – $t=8T_{op}/12$; j – $t=9T_{op}/12$; k – $t=10T_{op}/12$; l – $t=11T_{op}/12$; m – $t=T_{op}$

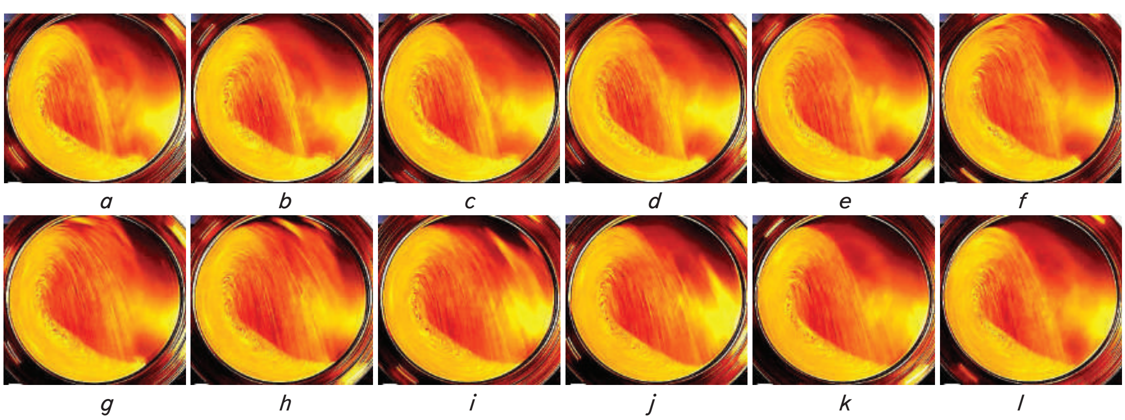
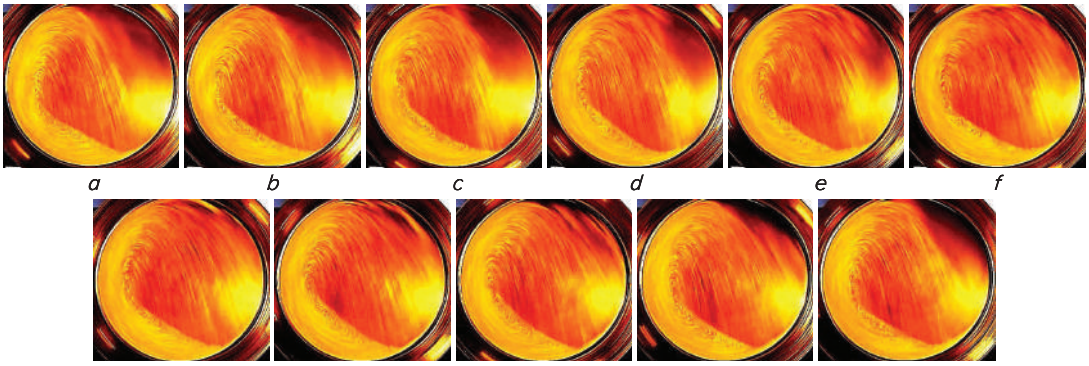


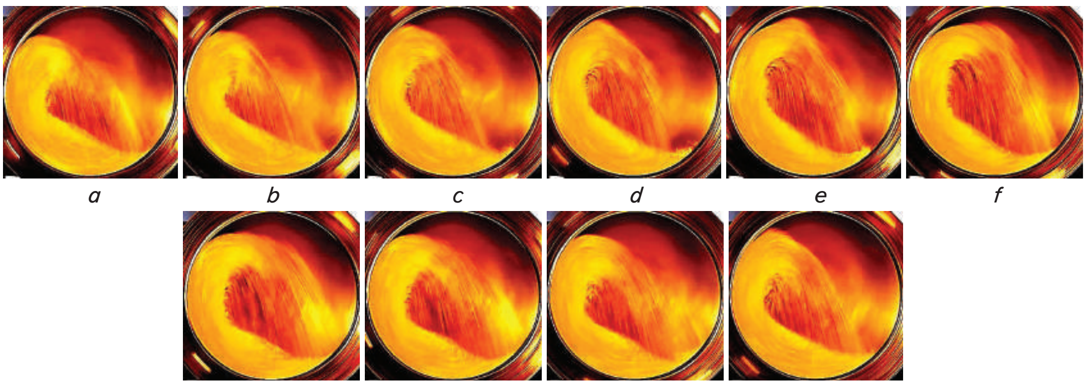
Fig. 6. Sequential load motion patterns over time t for one period of self-oscillations T_{op} at maximum scope at ψ_{db}=0,0104, $\psi_{dm}\approx 0.13\cdot 10^{-3}$, κ_{br}=0,35, κ_{mbgr}=0.25, and $\psi_{\omega}\approx 1$: a – t=0; b – $t=T_{op}/11$; c – $t=2T_{op}/11$; d – $t=3T_{op}/11$; e – $t=4T_{op}/11$; f – $t=5T_{op}/11$; g – $t=6T_{op}/11$; h – $t=7T_{op}/11$; i – $t=8T_{op}/11$; j – $t=9T_{op}/11$; k – $t=10T_{op}/11$; l – $t=T_{op}$



a b c d e f

g h i j k

Fig. 7. Sequential load motion patterns over time t for one period of self-oscillations T_{op} at maximum scope at ψ_{db}=0.0104, $\psi_{dm}\approx 0.13\cdot 10^{-3}$, κ_{br}=0.35, κ_{mbgr}=0.5, and $\psi_{\omega}\approx 1$: *a* – t=0; *b* – $t=T_{op}/10$; *c* – $t=2T_{op}/10$; *d* – $t=3T_{op}/10$; *e* – $t=4T_{op}/10$; *f* – $t=5T_{op}/10$; *g* – $t=6T_{op}/10$; *h* – $t=7T_{op}/10$; *i* – $t=8T_{op}/10$; *j* – $t=9T_{op}/10$; *k* – $t=T_{op}$



a b c d e f

g h i j

Fig. 8. Sequential load motion patterns over time t for one period of self-oscillations at maximum scope at ψ_{db}=0.0104, $\psi_{dm}\approx 0.13\cdot 10^{-3}$, κ_{br}=0.35, κ_{mbgr}=1, and $\psi_{\omega}\approx 1$: *a* – t=0; *b* – $t=T_{op}/9$; *c* – $t=2T_{op}/9$; *d* – $t=3T_{op}/9$; *e* – $t=4T_{op}/9$; *f* – $t=5T_{op}/9$; *g* – $t=6T_{op}/9$; *h* – $t=7T_{op}/9$; *i* – $t=8T_{op}/9$; *j* – $t=T_{op}$

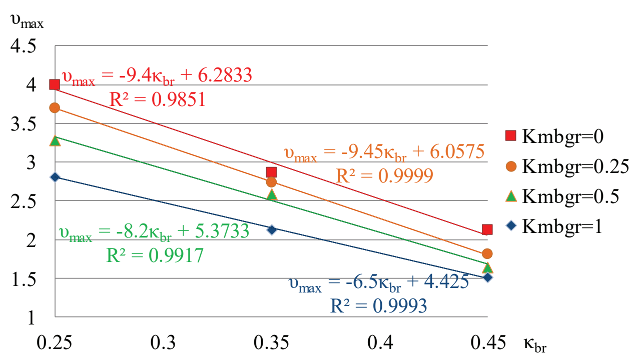


Fig. 9. Experimental dependence of change in the maximum load dilatancy value over one period of self-oscillations υ_{max} at ψ_{db}=0.0104, $\psi_{dm}\approx 0.13\cdot 10^{-3}$, κ_{mbgr}=0; 0.25; 0.5; and 1 on the degree of filling the chamber with particles of the large fraction at rest κ_{br}

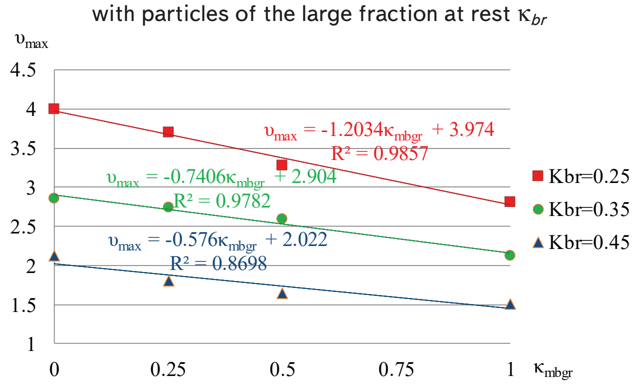


Fig. 10. Experimental dependence of change in υ_{max} at ψ_{db}=0.0104, $\psi_{dm}\approx 0.13\cdot 10^{-3}$, κ_{br}=0.25; 0.35; and 0.45 on the degree of filling the gaps between the particles of the large fraction with the particles of the fine fraction at rest κ_{mbgr}

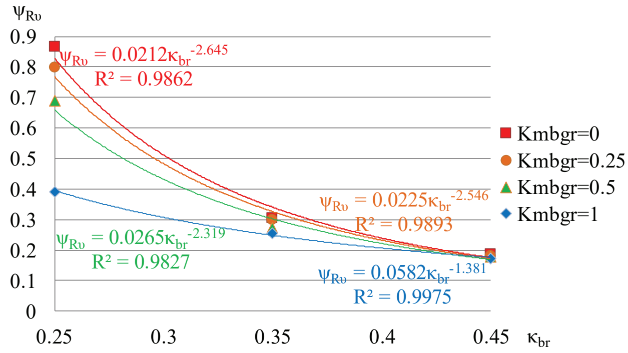


Fig. 11. Experimental dependence of change in the relative scope of the load's self-oscillations $\psi_{R\upsilon}$ at ψ_{db}=0.0104, $\psi_{dm}\approx$0.13·10^{-3}, κ_{mbgr}=0; 0.25; 0.5; and 1 on κ_{br}

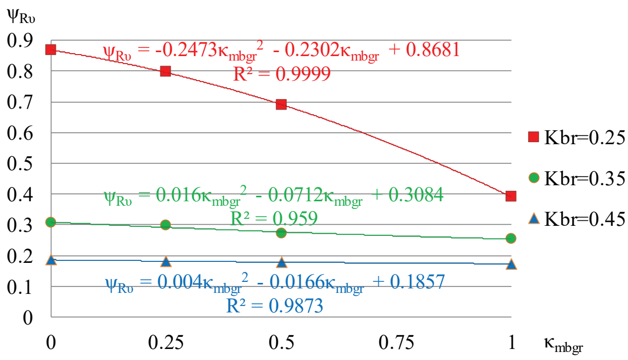


Fig. 12. Experimental dependence of change in $\psi_{R\upsilon}$ at ψ_{db}=0.0104, $\psi_{dm}\approx$0.13·10^{-3}, κ_{br}=0.25; 0.35; and 0.45 on κ_{mbgr}

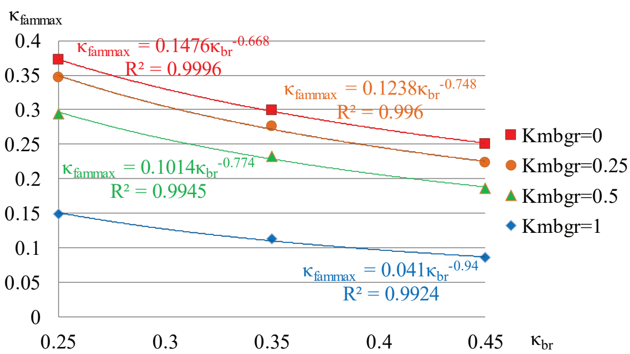


Fig. 13. Experimental dependence of change in the mass fraction of the active part of the load κ_{fammax} at ψ_{db}=0.0104, $\psi_{dm}\approx$0.13·10^{-3}, κ_{mbgr}=0; 0.25; 0.5; and 1 on κ_{br}

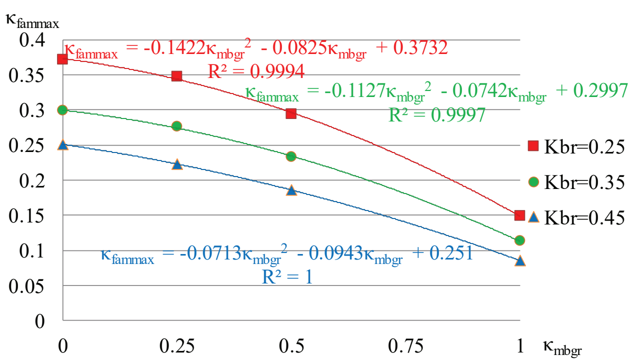


Fig. 14. Experimental dependence of change in κ_{fammax} at ψ_{db}=0.0104, $\psi_{dm}\approx$0.13·10^{-3}, κ_{br}=0.25; 0.35; and 0.45 on κ_{mbgr}

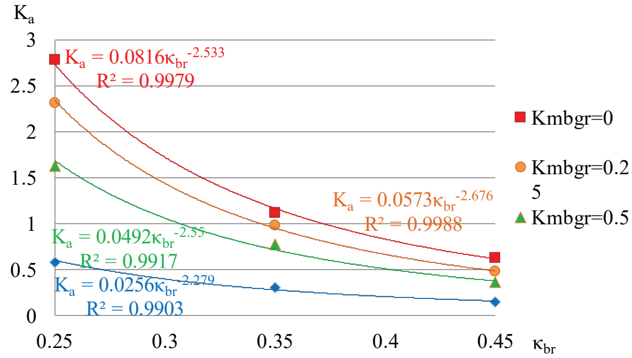


Fig. 15. Experimental dependence of change in the degree of dynamic activation of the load K_a at ψ_{db}=0.0104, $\psi_{dm}\approx$0.13·10^{-3}, κ_{mbgr}=0; 0.25; 0.5; and 1 on κ_{br}

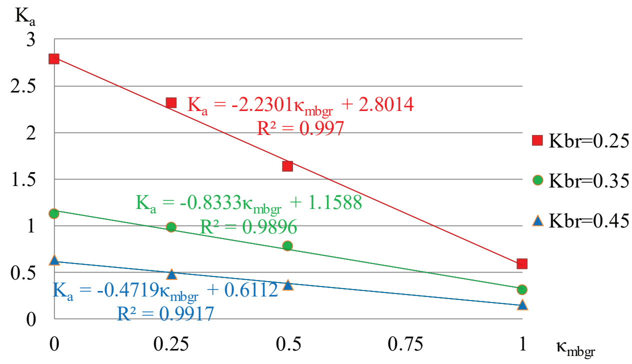


Fig. 16. Experimental dependence of change in K_a at ψ_{db}=0.0104, $\psi_{dm}\approx$0.13·10^{-3}, κ_{br}=0.25; 0.35; and 0.45 on κ_{mbgr}

The experimental dependences of numerical values of υ_{max}, $\psi_{R\upsilon}$, κ_{fammax}, and K_a characterize the effect of change in κ_{br} and κ_{mbgr} on the dynamic effect of self-oscillatory load.

5. 2. Results of determining the joint impact of filling the chamber and material content on milling

The charts showing the results from determining experimentally the change in process parameters on the degree of filling the chamber with grinding bodies and the content of the crushed material in the load are given in Fig. 17–20. The dependence of change in C_o/C_s on κ_{br} is shown in Fig. 17; C_o/C_s on κ_{mbgr} – in Fig. 18; E_o/E_s on κ_{br} – in Fig. 19; E_o/E_s on κ_{mbgr} – in Fig. 20.

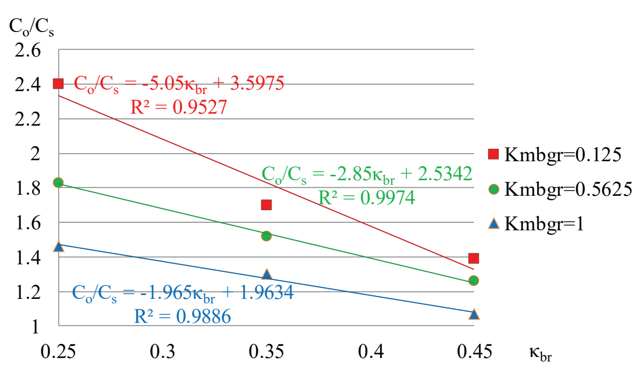


Fig. 17. Experimental dependence of change in the relative performance of the self-oscillatory process of grinding cement clinker in a tumbling mill C_o/C_s at ψ_{db}=0.026, ψ_{dm}<0.0059, κ_{mbgr}=0.125; 0.5625; and 1 on the degree of filling the chamber with grinding bodies at rest κ_{br}

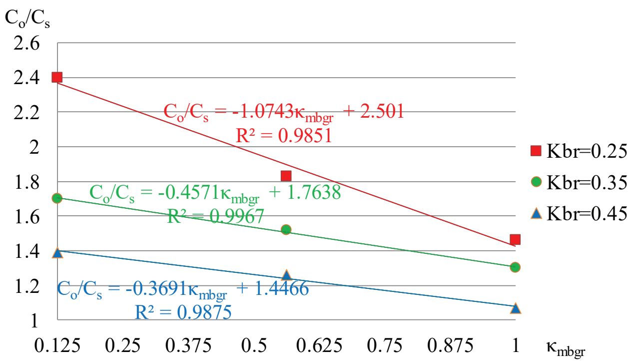


Fig. 18. Experimental dependence of change in C_o/C_s at ψ_{db}=0.026, ψ_{dm}<0.0059, κ_{br}=0.25; 0.35; and 0.45 on the degree of filling the gaps between grinding bodies with the particles of crushed material at rest κ_{mbgr}

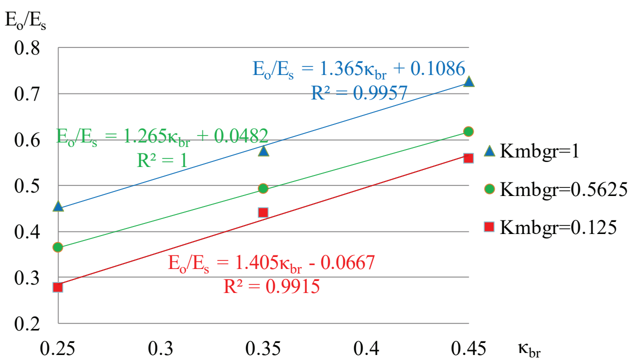


Fig. 19. Experimental dependence of change in the relative specific energy intensity of the clinker self-oscillatory grinding process in a tumbling mill E_o/E_s at ψ_{dm}=0.026, ψ_{dm}<0.0059, κ_{mbgr}=0.125; 0.5625; and 1 on κ_{br}

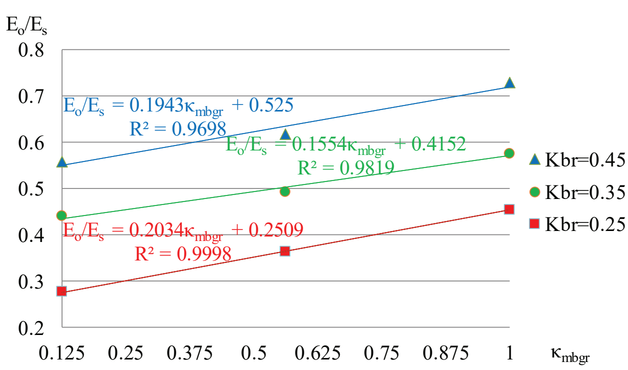


Fig. 20. Experimental dependence of change in E_o/E_s at ψ_{db}=0.026, ψ_{dm}<0.0059, κ_{br}=0.25; 0.35; and 0.45 on κ_{mbgr}

The dependences of numerical values of C_o/C_s and E_o/E_s characterize the joint effect of change in κ_{br} and κ_{mbgr} on the efficiency of the self-oscillatory grinding process in a tumbling mill.

6. Discussion of results of studying the joint impact of filling and the content of the material on the dynamic and technological parameters of self-oscillatory milling

Our results of the experimental visualization of the flow, as well as numerical data, have made it possible to qualitatively and quantitatively assess the impact of joint interaction between κ_{br} and κ_{mbgr} on the dynamic effect of a two-factional self-oscillatory load.

The comparative visual analysis of motion patterns in Fig. 1–4 clearly shows a decrease in the dynamic effect of self-oscillations of a two-fraction load with an increase in the content of the fine fraction κ_{mbgr}. With the growth of κ_{mbgr}, the scope of self-oscillations decreases, as well as the dilatancy and the active share of the load, while its passive share increases. The established decrease in the load's activity is predetermined by the increased binding properties of particles of a loose large fraction under the influence of particles of fine fraction. Such a connected influence causes the phenomenon of adhesion of the load near the wall of the chamber due to the sticking of layers and sticking to a hard wall.

Our analysis of motion patterns in Fig. 5–8 also shows a decrease in the dynamic activity of self-oscillations of a two-faction load with an increase in κ_{mbgr}.

However, it follows from a joint comparative analysis of patterns in Fig. 1–8 that the activity of self-oscillations already decreases with an increase in the degree of filling the chamber κ_{br}. At the same time, the scope of self-oscillations, the dilatancy and active particle also decrease, while the passive share of load increases. Strengthening the binding properties of a large fraction under the influence of a small fraction causes, in this case, the liquefaction phenomenon in the form of mutual slipping of the load's layers in the central part of the chamber.

Our analysis of charts in Fig. 9 confirms the growth of $\upsilon_{\max}$ with a decrease in κ_{br}. At the same time, the intensity of growth $\upsilon_{\max}$ is increasing with a decrease in κ_{mbgr}. It follows from Fig. 10 that $\upsilon_{\max}$ is growing with a decrease in κ_{mbgr}. At the same time, the intensity of growth in $\upsilon_{\max}$ is increasing with a decrease in κ_{br}.

Charts in Fig. 11 show an increase in $\psi_{R\upsilon}$ with a decrease in κ_{br}. At the same time, the intensity of growth in $\psi_{R\upsilon}$ is significantly increased with a decrease in κ_{mbgr}. It follows from Fig. 12 that $\psi_{R\upsilon}$ increases with a decrease in κ_{mbgr}. At the same time, the intensity of $\psi_{R\upsilon}$ increases with a decrease in κ_{br}.

Charts in Fig. 13 show an increase in $\kappa_{fam\max}$ with a decrease in κ_{br}. At the same time, the growth intensity of $\kappa_{fam\max}$ increases with a decrease in κ_{mbgr}. It follows from Fig. 14 that $\kappa_{fam\max}$ is increasing with a decrease in κ_{mbgr}. At the same time, the growth intensity of $\kappa_{fam\max}$ increases with a decrease in κ_{br}.

Our analysis of charts in Fig. 15 confirms a K_a growth with a decrease in κ_{br}. At the same time, the growth intensity of K_a is significantly increased with a decrease in κ_{mbgr}. It follows from Fig. 16 that K_a is growing with a decrease in κ_{mbgr}. At the same time, the growth intensity of K_a is significantly increased with a decrease in κ_{br}.

It was found that the dynamic effect of the joint interaction of these two factors κ_{br} and κ_{mbgr} significantly exceeds the sum of effects exerted by the action of individual factors. In particular, with a separate decrease in the degree of filling the chamber κ_{br} from 0.45 to 0.25, for the degree of filling the gaps between the spherical particles of a large fraction with particles of small fraction κ_{mbgr}=1, the value of $\upsilon_{\max}$ increases only by about 86 % (Fig. 9). With a separate reduction of κ_{mbgr} from 1 to 0, for κ_{br}=0.45, the value of $\upsilon_{\max}$ increases only by 40 % (Fig. 10). However, with a joint reduction of κ_{br} from 0.45 to 0.25 and κ_{mbgr} from 1 to 0, the value of $\upsilon_{\max}$ increases by 2.65 times (Fig. 9, 10). The corresponding increase in the values of $\psi_{R\upsilon}$ is 2.26 times (Fig. 11), 8 % (Fig. 12), and 5 times (Fig. 11, 12), for $\kappa_{fam\max}$ – 74 % (Fig. 13), 2.94 times (Fig. 14), and 4.36 times (Fig. 13, 14), for K_a – 3.86 times (Fig. 15), 4.18 times (Fig. 16), and 18.41 times (Fig. 15, 16).

The above testifies to a sharp increase in the dynamic effect of a two-fractional self-oscillatory load with a joint decrease in κ_{br} and κ_{mbgr} due to a significant decrease in the share of the passive quasi-solid zone, an increase in the share of the active pulsation zone of movement, and an increase in dilatancy. This is due to the manifestation of the established emergent dynamic effect, which is exacerbated by the simultaneous interaction of increasing the scope of self-oscillations and weakening the coherent properties of particles from a loose large fraction under the influence of particles of fine fraction.

We have experimentally assessed the effect of the joint change in κ_{br} and κ_{mbgr} on the performance and energy intensity of the self-oscillatory process of grinding in a tumbling mill compared to the parameters of the conventional established process.

The analysis of charts in Fig. 17 confirms the growth in C_o/C_s with a decrease in κ_{br}. At the same time, the growth intensity of C_o/C_s increases with a decrease in κ_{mbgr}. It follows from Fig. 18 that C_o/C_s is growing with a decrease in κ_{mbgr}. At the same time, the growth intensity of C_o/C_s increases with a decrease in κ_{br}.

Charts in Fig. 19 show the decline of E_o/E_s with a decrease in κ_{br}. It follows from Fig. 20 that E_o/E_s is declining with a decrease in κ_{mbgr}.

It turned out that the technological effect of the joint interaction of these two factors significantly exceeds the sum of effects exerted by the action of individual factors. In particular, with a separate reduction in κ_{br} from 0.45 to 0.25, at κ_{mbgr}=1, the C_o/C_s value increases only by about 37 % (Fig. 17) while the value of E_o/E_s decreases only by 50 % (Fig. 19). With a separate reduction in κ_{mbgr} from 1 to 0.125, atκ_{br}=0.45, the C_o/C_s value increases only by 30 % (Fig. 18) while the value of E_o/E_s decreases only by 39 % (Fig. 20). However, with a joint decrease in κ_{br} from 0.45 to 0.25 and κ_{mbgr} from 1 to 0.125, the C_o/C_s value increases by 125 % (Fig. 17, 18) while the value of E_o/E_s falls by 62 % (Fig. 19, 20).

This testifies to a sharp decrease in the specific energy intensity and a sharp increase in the productivity of the self-oscillatory grinding process due to a significant increase in the dynamic action of grinding load (Fig. 9–16). This is due to the manifestation of the established synergistic technological effect, which is exacerbated by the joint interaction of reducing the degree of filling the chamber with a load and the content of the crushed material in it.

We have also found a significant increase in the technological efficiency of the self-oscillatory process of grinding in tumbling mills with a decrease in the fineness of the final product, which is usually associated with the limitation of κ_{br} and κ_{mbgr}. In particular, for coarse milling, at κ_{br}=0.45 and κ_{mbgr}=1, C_o/C_s increased only by 7 % (Fig. 17, 18) while E_o/E_s decreased only by about 27 % (Fig. 19, 20). For medium milling, at κ_{br}=0.35 and κ_{mbgr}=0.5625, C_o/C_s grew by 52 % (Fig. 17, 18) while E_o/E_s fell by 49 % (Fig. 19, 20). However, for fine milling, at κ_{br}=0.25 and κ_{mbgr}=0.125, C_o/C_s increased by 140 % (Fig. 17, 18) while E_o/E_s decreased by 72 % (Fig. 19, 20).

The applicability of our results is defined by the following basic accepted limitations. The volumetric degree of filling the drum chamber with particles of the large fraction at rest in all studies was κ_{br}=0.25, 0.35, and 0.45. The results from the dynamic study (Fig. 1–16) were obtained at the content of particles of fine fraction in a two-fraction load of κ_{mbgr}=0, 0.25, 0.5, and 1, the relative size of particles of large fraction ψ_{db}=0.0104 and small fraction $\psi_{dm}\approx 0.13\cdot 10^{-3}$. The results from the technological study (Fig. 17–20) were obtained at the content of the crushed clinker in the load of κ_{mbgr}=0.125, 0.5625, and 1, the relative size of the grinding bodies ψ_{db}=0.026, and the particles of the source material ψ_{dm}<0.0059.

The limitations of the applied approach of assessing the impact of self-oscillations on the workflow include the disregard of bifurcation values for the control parameters of the dynamic tumbling mill system.

In the future, it is advisable to determine the qualitative and quantitative impact exerted on the dynamic and technological parameters of the process by the frequency characteristics of self-oscillations of the poly-grained load in the chamber of a rotating drum. That would make it possible to establish the rational conditions for the self-excitation of load's pulsations during the implementation of the self-oscillatory process of grinding in tumbling mills for various types of milling.

7. Conclusions

1. It was established that with a joint decrease in the degree of filling the chamber κ_{br} and the content of the small fraction κ_{mbgr}, the self-oscillatory dynamic action of a two-fraction load increases dramatically. With a separate reduction in κ_{br} from 0.45 to 0.25, for κ_{mbgr}=1, $\upsilon_{\max}$ increases by only 86 %. With a separate reduction in κ_{mbgr} from 1 to 0, for κ_{br}=0.45, $\upsilon_{\max}$ increases by only 40 %. However, with a joint reduction in κ_{br} from 0.45 to 0.25 and κ_{mbgr} from 1 to 0, $\upsilon_{\max}$ increases by 2.65 times. The corresponding growth for $\psi_{R\upsilon}$ is 2.26 times, 8 %, and 5 times, for $\kappa_{fam\max}$ – 74 %, 2.94, and 4.36 times, for K_a – 3.86, 4.18, and 18.41 times. This is due to a significant increase in the share of the passive quasi-solid zone, a decrease in the share of the active pulsation zone of movement in the cross-section of the chamber, and an increase in the load's dilatancy. This is predetermined by the manifestation of the established emergent dynamic effect, which is exacerbated by the simultaneous interaction of increasing the scope of self-oscillations and weakening the binding properties of particles of a loose large fraction under the influence of particles of fine fraction.

2. It was found that with a joint reduction in κ_{br} and κ_{mbgr}, the specific energy intensity is sharply reduced while the relative productivity of the self-oscillatory milling process is dramatically increased compared to the conventional established process. This is due to a significant increase in the dynamic effect of the grinding load on the crushed material. With a separate reduction in κ_{br} from 0.45 to 0.25, for κ_{mbgr}=1, E_o/E_s decreases only by 60 %. With a separate reduction in κ_{mbgr} from 1 to 0.125, for κ_{br}=0.45, E_o/E_s decreases by only 30 %. However, with a joint reduction in κ_{br} from 0.45 to 0.25 and κ_{mbgr} from 1 to 0.125, E_o/E_s decreases by 2.63 times. The corresponding growth for C_o/C_s is 73 %, 30 %, and 2.25 times. We have established a significant increase in the technological efficiency of the self-oscillatory grinding process in tumbling mills with a decrease in the fineness of the final product. For coarse milling, at κ_{br}=0.45 and κ_{mbgr}=1, the reduction in E_o/E_s is only 27 %, the increase in C_o/C_s is 7 %. For medium milling, at κ_{br}=0.35 and κ_{mbgr}=0.5625, E_o/E_s decreases by 49 %, C_o/C_s grows by 52 %. However, for fine milling, at κ_{br}=0.25 and κ_{mbgr}=0.125, the reduction in E_o/E_s is 72 %, the increase in C_o/C_s is 140 %. This is due to the manifestation of the established synergistic technological effect, which is exacerbated by the joint interaction of reducing the degree of filling the chamber with a load and the content of the crushed material in it.

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