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ТЕХНИКАЛЫҚ ҒЫЛЫМДАР ЖӘНЕ ТЕХНОЛОГИЯЛАР СЕРИЯСЫ / TECHNICAL SCIENCES AND TECHNOLOGY SERIES/ СЕРИЯ ТЕХНИЧЕСКИЕ НАУКИ И ТЕХНОЛОГИИ

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Approach for determination of geometric parameters of new oval design of rotor in innovative rotor-vibration type of mills

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Abstract. The principal disadvantages of mills utilised for fine and ultrafine grinding processes are the restricted product fineness and the low energy efficiency. As a solution of the problem, new principle of the grinding process and innovative design of rotor-vibration type of mill are proposed. The mill design is based on the Rebinder effect, which serves to reduce the particles strength and, consequently, increasing product fineness and energy efficiency. As an example of the rotor-vibration type of mill, the design including oval rotor, grinding media, vibration drive with spring elements is presented in the paper. The originality of the mill design is the oval shape of the rotor. However, due to the originality of the shape of oval rotor, there are no approaches to determining the geometric parameters of the rotor (major and minor semi-axis, height). Consequently, an approach is presented for determining the geometric parameters of a new oval-shaped rotor design in innovative rotary-vibratory type mills. The research results can be used in the design process of new mill designs based on rotor-vibration method of fine and ultrafine comminution.

Keywords: comminution process, bead mill, grinding media, geometric parameters, fineness of grinding, energy efficiency, mill design.

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Introduction

The fine and ultrafine grinding process is applied in many technological operations [1]. Mills that employ grinding media as an instrument for transferring collision energy for grinded particles is one of the most widespread types of mills widely used in various industries [2].

Among the mills with operational principle based on the "grinding media-particles" collision, the most popular types of mill are stirred mills and vibration mills. Stirred mill is characterized by capability of obtaining fine and ultrafine product particle sizes. This is the reason of why the design of stirred mill is considered to be as a successful option for replacement of traditional ball mill. The main components of stirred mills are chamber, rotor, grinding media, and an electric motor (see Fig. 1) [3]. The chamber is filled with grinding media and grinded material.

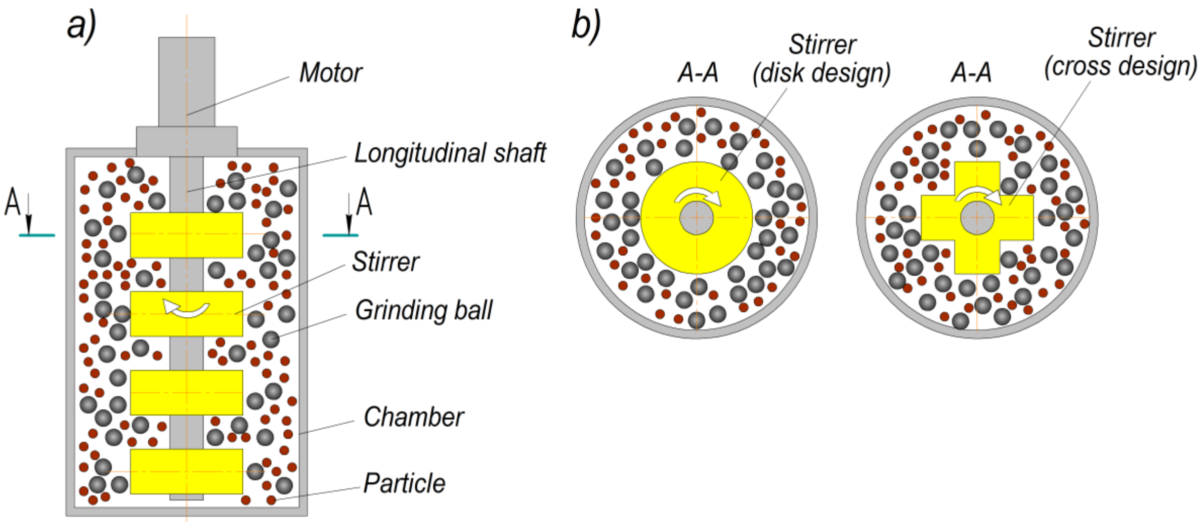

Figure 1. The traditional design of stirred mill

Note: compiled based on the data [3]

The electric motor contributes to the rotation of the rotor leading to the grinding media stirring. The comminution procedure is implemented owing to interaction between grinding media and the particles of grinded material [4].

However, as a result of design features the capability of providing high indexes of effectiveness (achieving the required product fineness and energy efficiency) is restricted in stirred mill. The reasons are connected with insufficient acceleration of grinding media caused by high chamber filling ratio, decrease in the concentration of grinding media in the zone of high kinetic energy, contradictions in the applying the shape of rotor. On the one hand, disk rotor provides high value of product fineness and energy efficiency. However, on the other hand, providing an intense circulation of grinding media using disk rotor is problematically. Thus, it should be resumed that the problem of increase in comminution process efficiency lies behind the design features of stirred mill.

The vibration mill consists of chamber, grinding media, and a vibration drive (see Fig. 2) [5].

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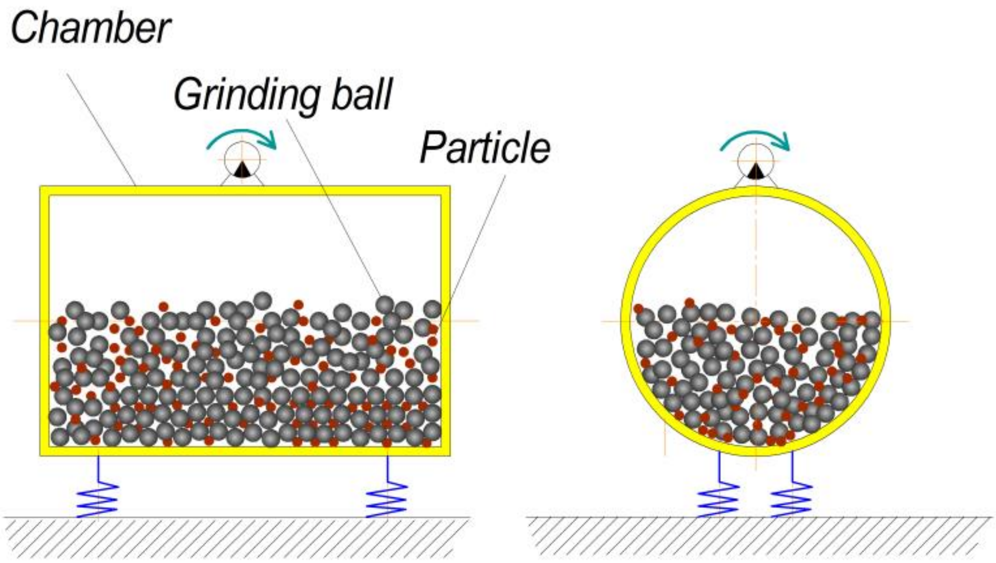


Figure 2. The parts of vibration mill

Note: compiled based on the data [5]

Vibration of the chamber leads to periodic collision of the grinding media with particles and, consequently, contributes to the reduction of particles size [6]. However, the design features of the vibration mill, increase in collision energy of grinding media is restricted. Thus, it is necessary to reconsider design of mill to increase the grinding efficiency.

In order to increase in efficiency of comminution process, new rotor-vibration type of mills is proposed [5]. The proposed rotor-vibration type of mills contributes periodic compressive and tensile stresses in the particle leading creation of Rebinder effect (decrease in the strength of the material due to the organization of alternating loads in the particle) (see Fig. 3).

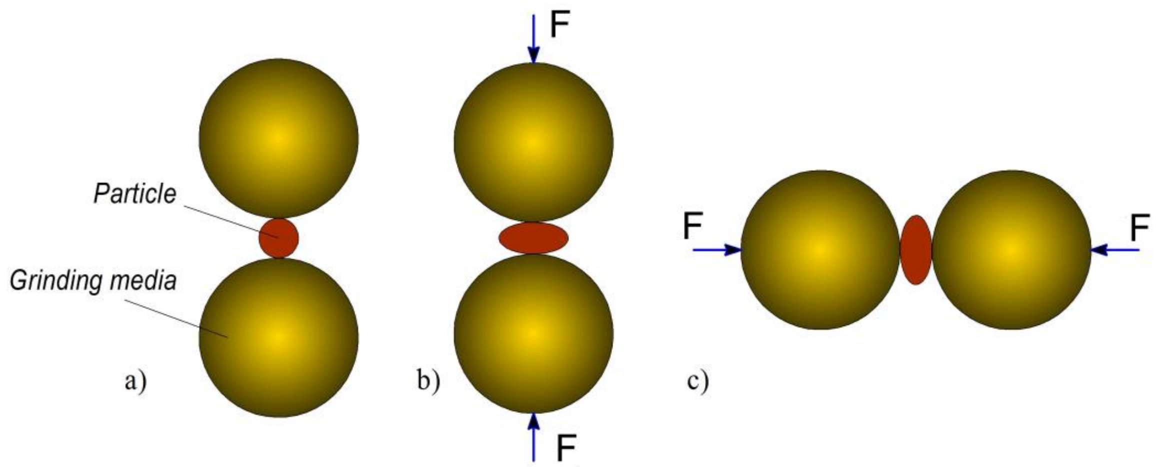


Figure 3. The principle of comminution in the new design of mill

Note: compiled based on the data [5]

The example of rotor-vibration mill design is illustrated in Fig. 4. The design of the mill comprises chamber, oval rotor, grinding media, electric motor, vibration drive, and spring elements [7]. The combination of the proposed design elements provides collisions of the grinding media in radial and axial directions.

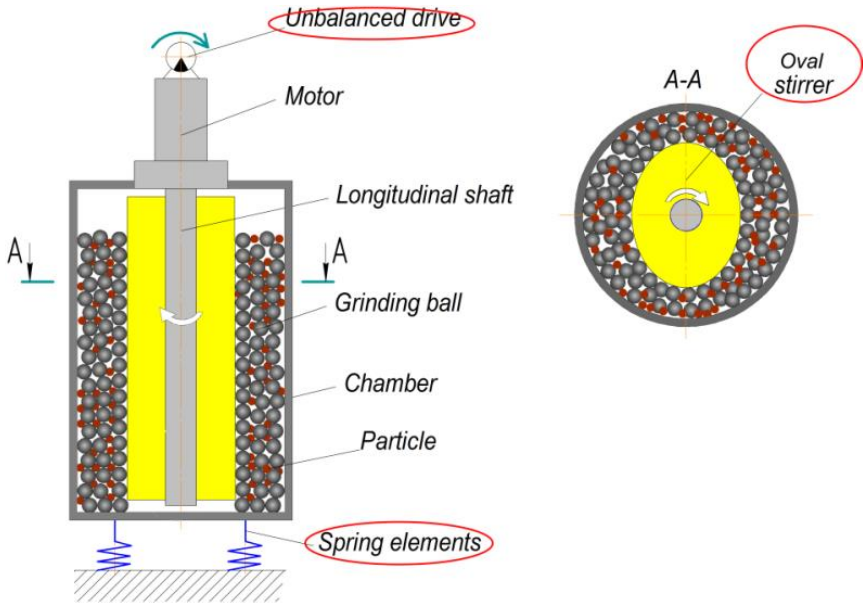


Figure 4. The proposed design of stirred mill

Note: compiled based on the data [3]

The design feature of the proposed mill is an oval rotor. The geometric parameters of the oval rotor are major semi-axis and minor semi-axes. Taking into account the fact that the design of the rotor is new, it is necessary to develop the approach for determination of the geometric parameters of rotor in dependence on energy consumption of the mill. Taking into account the operation principle of the mill the effect of the oval rotor parameters on the energy consumption of the mill should be conducted in combination with chamber diameter, grinding media filling ratio, and grinding media size.

The results of literature review showed that a range of papers dedicated to investigation of effect the geometric parameters on the efficiency of grinding process are conducted by other authors. One of the geometric parameters is chamber diameter. In the work [8], the principle of determination of the chamber diameter in stirred mills is considered. The investigation results showed that chamber diameter should be assign from providing maximum distance between rotor edge and chamber wall. The authors of the work [9] investigated the approach for determination of the chamber diameter depending on the technological and economic effectiveness of mineral material grinding in electromagnetic mill.

A set of research are dedicated to the investigation of the effect of the rotor design on the efficiency of the grinding process. For example, in the work [8], disk, wing and cross types of rotor design are investigated. The investigation results showed that disk rotor is characterized by higher energy efficiency. The wing and cross rotors contribute to the intensive stirring process leading to increase in grinding efficiency. In the work [10], the geometric parameters of pin rotor are investigated. The research results showed that with increase in pin numbers, the grinding efficiency increases. However, increase in pin numbers lead to increase in energy consumption.

A set of investigations are dedicated to the selection of the grinding media size. In the paper [11], the authors proposed the approach for determination of the grinding media size comparing the process of the particle size reduction in stirred mills with crushing process of the piece of material in roller crusher. As a result, it is recommended to select the grinding media size based on the observance of the ratio of the grinding media size and the particle size of 20:1. The authors of the work [12] investigated the dependence between grinding media diameter and the amount of required energy. The research results showed that using the four groups of grinding media (19.5, 38 mm; 19.5, 50 mm; 38, 50 mm and 19.5, 38, 50 mm) the required energy is close in values. In the work [13], the approach for determination of the grinding media diameter in vibration mill is presented. According to the approach, the grinding media diameter is selected based on the desired grinding time. For example, applying 15 mm grinding media, compared to 12 mm, resulted in a 22.5% reduction in grinding time to achieve a product fineness of 0–10 μm.

A number of studies are connected with research of the chamber grinding media filling ratio. In the work [14], the effect of the grinding media filling ratio on the efficiency of the grinding process is investigated. According to the results, increase in media filling ratio, the number of grinding media collisions increases, however, the space for media acceleration is decreased. The authors of the work [15] set the mathematical dependence between grinding media filling ratio and required power and productivity of an industrial ball mill. The dependence leads to select the value of grinding media filling ratio. In the work [16], the authors propose new approach for calculation of the grinding media filling of the chamber. The approach includes new equations for determination of the grinding media filling ratio considering the volume in the conical ends and the volume occupied by the mill shell lifters. The authors of the work [17] investigate the effect of the grinding media filling ratio on the product fineness and energy consumption. The results of the research showed that while grinding media filling ratio increases, the grinding process efficiency increases.

However, the problem is that the existing approaches cannot be used for determination of the geometric parameters of the new type of mill called “rotor-vibration mills”. Presenting the current investigations as a model of “black box”, while the input of the system is geometric parameters of the oval rotor (major semi-axis, minor semi-axis), output is energy consumption of the grinding process.

The aim of this paper is to investigate new approach for determination of the geometrical parameters of the innovative design of oval rotor capable of increasing the product fineness and diminish energy consumption for comminution process.

The methodology

The geometrical parameters of the oval rotor are major and minor semi-axes. In order to justify aforementioned geometric parameters, it is necessary to accept some of parameters. Let us accept that initial particle size is 100 μm as an initial boundary value of fine grinding. Based on the previous investigations conducted by other authors [18], the range of grinding media sizes applied in stirred media is 1.5…10 μm. Taking into account the fact that it is necessary to provide maximum productivity of the mill, let us accept that grinding media size is 10 mm.

In order to achieve effectiveness of the grinding process, it is necessary to provide placement at least two grinding media in the space between rotor extreme point and chamber wall, i.e.:

$$0{,}5D_{CH} - b \geq 2d_{\mathrm{GM}} \tag{1}$$

Determination of the chamber diameter is conducted based on the required value of productivity Q of the proposed design of mill. The mill productivity Q defined as the volume of the grinded material per unit of time can be evaluated by the following formula:

$$Q = \frac{V_Q \cdot N_Q}{t_Q}. \tag{2}$$

In Eq. (2), V_Q is the volume of interspherical channels, N_Q is the number of interspherical channels. According to the model, the grinded material moves through interspherical channels in a top-down direction over time [19]:

$$t_Q = \sqrt{\frac{2H_Q}{g}} \cdot K_{\mathrm{res}}, \tag{3}$$

In Eq. (3), N_Q is the total height of grinding media in the mill chamber, mm; K_{res} is coefficient of resistance to free movement of material leading to increase time t_Q $(K_{\mathrm{res}} = 2.66)$; g is acceleration of gravity $(g = 9{,}81\ \mathrm{m/s}^2)$.

The value of the volume V_Q of one interspherical channel is calculated by multiplying the channel area S_Q and height H_Q:

$$V_Q = S_Q \cdot H_Q. \tag{4}$$

The calculation of the area S_Q is conducted by difference of the area of an equilateral triangle ΔABC and areas of three sectors I, II and III. (Fig. 5):

$$S_Q = 0.0403 d_{\mathrm{GM}}^2 \tag{5}$$

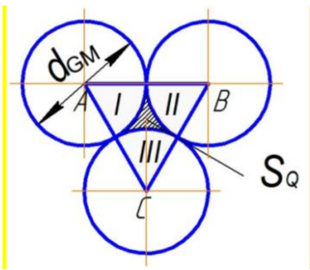


Figure 5. Interspherical channel

Note: compiled based on the data [19]

The total height of the grinding media in the chamber is determined by the following formula:

$$H_Q = \frac{2N_{\text{GM}} \cdot d_{\text{GM}}^2}{D_{CH}} \quad (6)$$

Based on Eqs. (5) and (6):

$$V_Q = \frac{0.0806 \cdot N_{\text{GM}} \cdot d_{\text{GM}}^4}{D_{CH}} \quad (7)$$

The total number of interpherical channels can calculated using the following formula:

$$N_Q = \frac{\sum V_{\text{por}}}{V_Q} \quad (8)$$

In Eq. (8), $\sum V_{\text{por}}$ is the volume of porosity. In order to calculate the parameter of $\sum V_{\text{por}}$ grinding media position is modelled as presented in Fig. 6.

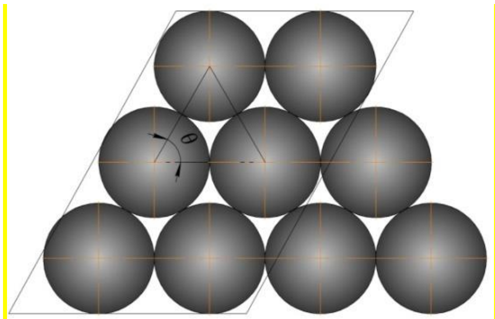


Figure 6. The scheme of grinding media position

Note: compiled based on the data [19]

As it follows from Fig. 6, space (porosity) is formed between the grinding media. The volume of the porosity can be calculated by the following formula:

$$\sum V_{\text{por}} = k_{\text{por}} \cdot \sum V_{\text{GM}}, \quad (9)$$

In Eq. (9), k_{por} is porosity coefficient. k_{por} =0,259 for rhombic configuration of grinding media; $\sum V_{\text{GM}}$, is the total volume of grinding media, mm^3.

Porosity coefficient k_{por} can be determined using Slichter's formula [19]:

$$k_{\text{por}} = 1 - \frac{\pi}{6 \cdot (1 - \cos\theta)\sqrt{1 + \cos\theta}}, \quad (10)$$

In Eq. (10), θ is the angle of intersection of the lines connecting the centers of the grinding media. With a rhombic configuration of media, $\theta = 60^0$. In this case, $k_{\text{por}} = 0.259$.

The total volume of the grinding media is determined by the following formula:

$$\sum V_{\text{GM}} = N_{\text{GM}} \cdot V_{\text{GM}} = 4.1888 \cdot N_{\text{GM}} R_{\text{GM}}^3, \quad (11)$$

In Eq. (11), V_{GM} is the volume of one grinding media, mm³ ($V_{\text{GM}} = \frac{4}{3}\pi R_{\text{GM}}^3$).

Taking into account Eqs. (8) and (9), Eq. (7) can be presented by the following way:

$$\sum V_{\text{por}} = 1.0849 \cdot N_{\text{GM}} R_{\text{GM}}^3 \quad (12)$$

Based on Eqs. (7) and (12), Eq. (8) can be presented as

$$N_Q = \frac{1.68 \cdot D_{\text{CH}}}{d_{\text{GM}}} \quad (13)$$

Taking into account Eqs. (7) and (13), the theoretical productivity of the the proposed mill is determined by the following formula:

$$Q = \frac{0.0677 \cdot d_{\text{GM}}^2 \cdot \sqrt{D_{\text{CH}} \cdot g}}{K_{\text{res}}} \quad (14)$$

Based on Eq. (14), chamber diameter is calculated by the following way:

$$D_{CH} = \frac{Q^2 \cdot K_{\text{res}}^2}{0.0045 \cdot d_{\text{GM}}^4 \cdot g}. \quad (15)$$

Then, based on Eq. (1), the formula for calculation major semi-axis can be presented as

$$b = 0.5 D_{CH} - 2 d_{GM}. \quad (16)$$

Findings/Discussion

Let us accept that targeted value of mill productivity is $Q = 10$ kg/h. In this case, according to Eq. (18), the diameter chamber is $D_{CH} = 120$ mm. The grinding media diameter $d_{\text{GM}} = 10$ mm. Then, based on the Eq. (1), the value of major semi-axis of oval rotor is $b = 40$ mm. Let us determine the value of minor semi-axis c varying in the range of $40 \text{ mm} < c \leq 2$ mm. The justification of the value of minor semi-axes is based on the calculation of the product fineness and theoretical power expended for grinding media circulation.

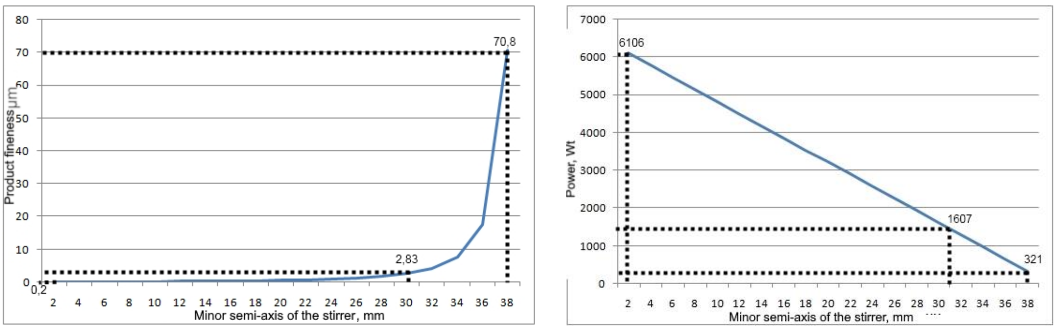
In Table 1, the results of calculation of the product fineness and theoretical power depending on the minor semi-axis varying are presented. The calculation of the values of product fineness and theoretical power presented in Table 1 is conducted using mathematical model developed by the authors of this paper presented in [19].

Table 1. Results of calculation of the dependence of theoretical product fineness and power for circulation of grinding media on the value of the minor semi-axis of an oval rotor [19]

c, mm	Product fineness, µm	Power, Wt
2	0.2	6106
4	0.22	5785
6	0.25	5463
8	0.28	5142
10	0.31	4820
12	0.36	4499
14	0.41	4178
16	0.49	3857
18	0.58	3535
20	0.7	3214
22	0.87	2893
24	1.1	2571
26	1.44	2250
28	1.97	1928
30	2.83	1607
32	4.43	1286
34	7.86	964
36	17.7	643
38	70.8	321

Note: compiled based on the data [19]

As it follows from Table 1, change the value of minor semi-axis from 2 mm to 38 mm leads to the change of the power from 321 Wt ($c = 38$ mm) to 6106 Wt ($c = 2$ mm). In Fig. 7, the graph of dependence of product fineness and power on the value of minor semi-axis is depicted.



a) dependence of the product fineness on the value of minor semi-axis of the rotor,
b) dependence of the power on the value of minor semi-axis of the rotor

Figure 7. The graph of dependence of product fineness and power on the value of minor semi-axis

Note: compiled based on the data [19]

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It is obviously that the value of $c = 2$ mm corresponds to the maximum product fineness (0.2 μm). However, the power expended for grinding media circulation increases. Therefore, the value of minor semi-axis is selected based on the condition of providing product fineness not less than 5 μm and rational value of power expenditures. Therefore, let us accept that the value of semi-minor axis of oval rotor is $c = 30$ mm. Thus, the parameters of oval stirrer are major semi-axis $c = 30$ mm and minor semi-axis $b = 40$ mm.

The parameters of the spring elements are calculated based on the standard methods [20]. According to the calculations, number of turns of one spring is 6, spring diameter is 64 mm, thickness of spring coil is 6 mm, and spring stiffness coefficient is 8085 kN/mm^2.

Conclusion

In this paper, geometrical parameters of new design of oval stirrer used in innovative rotor-vibration type of mill are investigated and determined. New design of mill provides more effective comminution process on the criteria of product fineness and energy efficiency. The features of the new design are using oval rotor and vibration drive with spring elements. The improvement of the design of mill leads to periodic compressive and tensile stresses in the particle that contributes creation of Rebinder effect. The results of investigations showed that the value of major semi-axis of ellipsoidal rotor is 40 mm, the value of minor semi-axis of ellipsoidal rotor is 30 mm. The parameters of the oval rotor are defined based on providing required product fineness and minimal energy consumption. The investigations results can be used in the process of production of effective design of rotor-vibration type of mill providing high product fineness and energy efficiency.

Acknowledgement, conflict of interests

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The contribution of the authors.

Baigereyev S. is responsible for development of the mill design, development of the approach for determination of the geometric parameters in the new type of mill.

G. Guryanov participates as a scientific consultant under conduction the research.

A. Suleimenov is responsible for literature review.

R. Gabdyssalyk is consultant on the development of the design of mill.

Nomenclature

D_{CH} Chamber diameter

b Major semi-axis of oval rotor

c Minor semi-axis of oval rotor

d_{GM}	Grinding media diameter
Q	Mill productivity
V_Q	Volume of interspherical channels
N_Q	Number of interspherical channels
t_Q	Time of movement of the grinded material through interspherical channels
H_Q	Total height of grinding media
K_{res}	Coefficient of resistance to free movement of material
g	Acceleration of gravity
N_{GM}	Number of grinding media
φ_{GM}	Chamber filling ratio with grinding media
k_{por}	Porosity coefficient
$\sum V_{\text{GM}}$	Total volume of grinding media (without porosity)
$\sum V_{\text{por}}$	Volume of the porosity
θ	Angle of intersection of the lines connecting the centers of the grinding media
R_{GM}	Grinding media radius

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Инновациялық роторлы-діріл диірмендерінде жаңа сопақ ротордың конструкциясының геометриялық параметрлерін анықтау тәсілі

Аңдатпа. Ұсақ және аса ұсақ ұнтақтау процесінде қолданылатын диірмендердің негізгі кемшіліктері ретінде өнімнің ұсақталу дәрежесінің шектелуі мен энергия тиімділігінің төмендігі атап өтіледі. Бұл мәселені шешу үшін ұнтақтау процесінің жаңа принципі мен ротор-вибрациялық типтегі диірменнің инновациялық жобасы ұсынылады. Диірменнің жобасының негізі – бөлшектердің беріктігін төмендететін және нәтижесінде өнімнің ұсақталу дәрежесі мен энергия тиімділігін арттыратын Ребиндер әсері. Ротор-вибрациялық типтегі диірменнің мысалы ретінде, мақалада сопақ роторды, ұнтақтаушы ортаны, серіппелі элементтері бар вибрациялық жетек жүйесін қамтитын конструкция ұсынылады. Диірмен жобасының ерекшелігі оның араластырғышының сопақ пішінінде жатыр. Дегенмен, сопақ ротор пішінінің ерекшелігіне байланысты, ротордың геометриялық параметрлерін (негізгі және кіші жартыосі, биіктігі) анықтауға қатысты ешқандай әдістер жоқ. Осыған байланысты инновациялық ротор-вибрациялық типтегі диірмендердегі жаңа сопақ конструкцияның геометриялық параметрлерін анықтау әдісі ұсынылады. Зерттеу нәтижелері жаңа диірмен конструкцияларын жобалау процесінде, ұнтақтаудың ұсақ және аса ұсақ әдісі негізінде қолданылуы мүмкін.

Түйін сөздер: ұсақтау процесі, бисерлік ұсақтағыш, ұнтақтау ортасы, геометриялық параметрлер, өнімнің ұсақтығы, энергия тиімділігі, ұсақтағыштың конструкциясы.

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Подход к определению геометрических параметров новой овальной конструкции ротора в инновационных мельницах роторно-вибрационного типа

Аннотация. Среди основных недостатков мельниц, используемых для процесса тонкого и сверхтонкого измельчения, выделяются ограниченная тонкость продукта и низкая энергетическая эффективность. В качестве решения проблемы предлагается новый принцип процесса измельчения и инновационное решение конструкции мельницы роторно-вибрационного типа. В основе конструкции мельницы – эффект Ребиндера, снижающий прочность частиц и, следовательно, увеличивающий тонкость продукта и энергетическую эффективность. В качестве примера мельницы роторно-вибрационного типа в статье представлена конструкция, включающая овальный ротор, измельчающие тела и вибрационный привод с пружинными элементами. Оригинальность конструкции мельницы заключается в овальной форме ротора. Однако, из-за оригинальности формы овального ротора, отсутствуют подходы для определения геометрических параметров ротора (большая и малая полуоси, высота). В связи с этим, представлен подход для определения геометрических параметров новой овальной конструкции ротора в инновационных мельницах роторно-вибрационного типа. Результаты исследования могут быть использованы в процессе проектирования новых конструкций мельниц, основанных на роторно-вибрационном методе тонкого и сверхтонкого измельчения.

Ключевые слова: процесс измельчения, бисерная мельница, мелющие тела, геометрические параметры, тонкость помола, энергоэффективность, конструкция мельницы.

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