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THE CHOICE OF DESIGN FEATURES FOR RING-BALL MILLS

The paper discusses a way of choosing the design features (geometry, the rate of grinding and thrust) of ring-ball mills. Various methods of calculating the optimal rate of grinding have been compared. Basing on experimental investigations on the pilot-plant and industrial scale, the influence of the angular velocity and the thrust on the mill have been verified, and the interdependence between the rate of grinding and the thrust of the grinding elements have been explained.

SPECIFICATION OF THE MOST IMPORTANT SYMBOLS

B – efficiency of the mill (flux of coal, dust at the same stipulated moisture), g/sec (kg/sec),

B_k – flux of material to be ground, drawn in by the balls (in the circumferential direction), kg/sec,

B_m – flux of material to be ground passing through the grinding assembly (in the radial direction), kg/sec,

d, D – diameter, m,

D_x – mass fraction of particles smaller than x (passing through a screen with a mesh equal to x), %,

e – unit of energy consumption (without taking into account idle running), J/g,

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f_k – thickness of the layer of the ground material under the balls, mm,
g – gravitational acceleration, m/sec^2,
N – power rating supplied to the motor of the mill, kW,
P – total thrust on the grinding surface, kN,
r, R – co-ordinate, radius, m,
R_x – mass fraction of particles with dimensions exceeding x (retained on the screen with a mesh of x dimensions), %,
s – thrust per unit on the crushing surface, kPa,
t – temperature of the drying and transporting medium, °C,
u – velocity of transportation, m/sec,
V – flux of drying and transporting gas, g/sec,
x – particle size (mesh), mm or μm,
z_k – number of balls,
Δp_m – drop of static pressure in the mill, kPa,
Δp_s – drop of static pressure down the height of the assembly (unit), brought about by the presence of particles of the ground material, kPa,
α – local co-ordinate of the crushing surface (angle of the path),
μ – coefficient (number) of friction of coal,
ρ – radius of the raceway (path), m,
ω – angular velocity of the crushing ring, 1/sec.

SUPERSCRIPTS:
m, *max* – maximum, *min* – minimum.

SUBSCRIPTS:
k – balls, mill chamber, *m* – mill, ground material, *r* – co-ordinate,
s – concerning solid particles of the mixture, *w* – internal,
z – external, A, B, C, D, E, P – characteristic geometrical points.

1. Introduction

In order to grind hard coal, mainly mediumspeed ring-ball mills (grinders) are applied in Polish power engineering. The newly introduced low-emission technique of combustion in energy boilers generally required a reduction of the grain size of pulverized coal supplied to the burners to such an extent that the content of combustible substances in the ash might be maintained on a permissible level. If the granulation of the dust was further reduced, the maximum efficiency of the mills decreased, involving a higher resistance of flow inside the installation, a higher consumption of energy and a shorter lifetime of the grinding elements. In order to adapt grinding installations to the requirements of environment protection, new higher effectivity grinding equipment was introduced. It is based on the idea of applying fewer balls, but with a larger diameter, as well as wider cyclone sifters permitting a more efficient separation.

The operational characteristics of mills are of great importance in the exploitation of the boiler, its availability and ecological features. Despite their wide application in energy engineering, the phenomena occurring in the course of grinding have not been fully recognized so far. Neither are there any universal methods of designing and determining the characteristics, connecting their efficiency with their fundamental design features. Hence, the necessity of investigating the phenomena of grinding on an experimental test stand provided with a ring-ball mill. Such investigations have been taken up at the Institute of Power Engineering and Turbomachinery of the Silesian University of Technology.

The influence of the design features of ring-ball mills (the geometry of the grinding equipment, rotational speed and thrust of grinding elements) on their efficiency has not been determined explicitly. Assessments of the optimal rate of grinding differ [9, 10]. The rates applied in Polish ring-ball mills are much higher than in the case of ring-roller mills of the type MPS [11]. Hence the problem of the proper choice of the geometrical characteristics, the angular velocity and thrust of the grinding elements aiming at the intensification and optimization of the process of grinding.

2. The proper choice of the design features

The geometry of the grinding equipment

In the method of calculations applied in this country, it has been assumed that the efficiency of the mill is proportional to the flux of coal drawn in by the balls ($B \sim B_k$). The flux under the balls is proportional to the length of the raceway arc $\rho_k(\alpha_A + \alpha_B)$, the thickness of the layer f_k and the rate of grinding $u_k = u/2$ (Fig. 1). For geometrically similar units with the same dimensionless velocity of the ring of Froude's number ($Fr_P = \omega^2 r_P/g$), the dependence of efficiency on the geometry of the grinding unit is expressed by the product (1) [2]:

$$B = C z_k d_k^2 \sqrt{D_P}; \qquad C - \text{constant quantity} \tag{1}$$

If the balls are closely arranged on the raceway of the ring, the following geometrical relation between the pitch diameter D_P, the diameters of the balls and their numbers z_k must be taken into consideration:

$$d_k = D_P \sin\frac{\pi}{z_k} \tag{2}$$

The pitch diameter D_P denotes the mean diameter of the path of the balls.

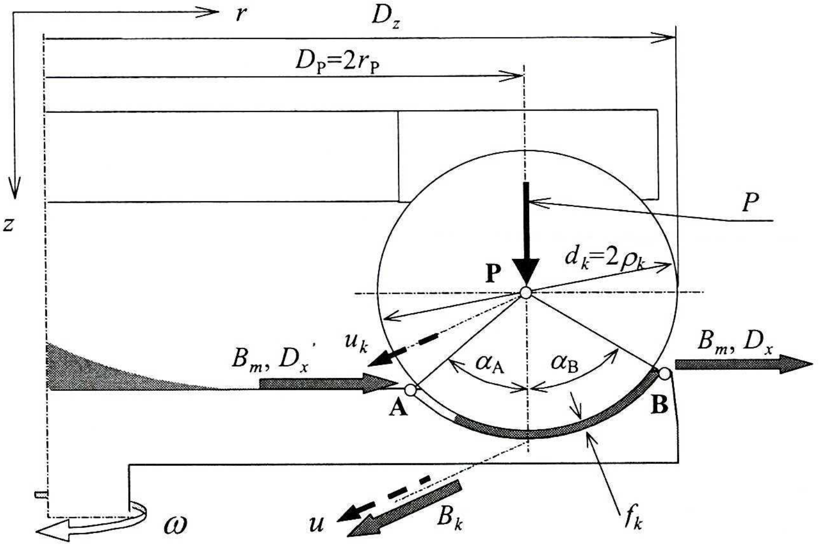

Fig. 1. Characteristics of the ball and race unit

Substituting this geometrical relation into (1) and maintaining the same external diameter of the grinding unit $D_z = D_P + d_k =$ idem (Fig. 1), we get the dependence of the efficiency on the number of balls $B = B(z_k)$ [6]:

$$B = Cz_k \frac{D_z^{2.5}(\sin(\pi/z_k))^2}{(1 + \sin(\pi/z_k))^{2.5}} \tag{3}$$

The maximum value is attained when $z_k = 5 \div 6$ balls.

Investigations on the test stand [4], followed by industrial ones, confirmed the influence of reduction of the number of balls on the efficiency of the grinding unit. Maintaining the same external diameter of the grinding unit D_z, the reduction of the number of balls from ten to seven resulted in an increase of the maximum efficiency by about 10%. Some of the MKM-25 and EM-70 mills applied in Polish power plants, in which such units are used, have already been reconstructed, where needed, replacing them either by nine balls or six ball units with ball diameters of 750 mm.

The rate and thrust of the grinding elements

The author of [10] determined the angular velocity ω by a simple model of flow of coal particles on the rotating ring, basing on the condition that the flux of coal ground by balls B_k and the flux of coal reaching the raceway in the radial direction B_m are equal. In this description it has been assumed that the grinding is accomplished along the whole arc of the raceway $\rho(\alpha_A + \alpha_B)$. The dimensionless velocity of the ring, related to the pitch radius of the raceway Fr_P amounts to:

$$Fr_P = \frac{4\mu_b}{4 - \alpha_A - \alpha_B}; \qquad \mu_b = \ln\frac{\cos(\alpha_B - \operatorname{arc\,tg}\mu)}{\cos(\alpha_A + \operatorname{arc\,tg}\mu)}, \tag{4}$$

The coefficient μ_b displays the character of a generalized friction index, taking into account the shape (inclination) of the raceway of the ring.

The authors of [7] and [9] assumed that grinding does not take place along the entire arc of the raceway, but only on some part of it. The determination of the optimal rate of grinding [9] is the curve of the flow stagnation of coal on the raceway (Fig. 2), without analyzing the variations occurring in the flux ground by the balls.

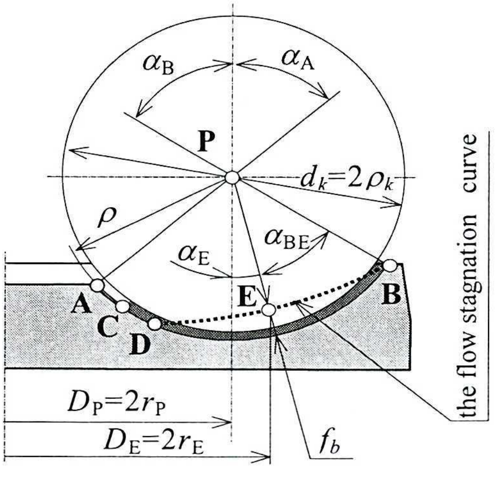

Fig. 2. Active raceway arc in the simulation of milling

The local inclination of the rotating conical surface α is determined basing on the condition of the equilibrium of forces affecting the mass element on the surface of the relative motionless material. The coal between the flow stagnation curve and the raceway, moving with the same velocity as the velocity of the ring, is subjected to grinding. Assuming that DB is a straight line, the thickest layer covering the raceway is $f_b = \rho(1 - \cos\alpha_{BE})$, and the maximum height of the layer dragged under the balls is $-f_k \approx 0.1\ \rho$. Comparing both these quantities, the mean value of the angle of inclination amounts to $\alpha_{BE} = 0.451$ (25.8°). Taking into account the fact that $\alpha_F = \alpha_B - \alpha_{BE}$ and substituting it in the equation of the surface of flow stagnation, the optimal dimensionless velocity will amount to:

$$Fr_E = \frac{\operatorname{tg}(\alpha_B - \alpha_{BE}) + \mu_w}{1 - \mu_w \operatorname{tg}(\alpha_B - \alpha_{BE})}, \tag{5}$$

Attention should be drawn to the fact that the quantity Fr_E concerns the radius $r_E = r_P + (\rho - f_b)\sin(\alpha_E)$ – Fig. 2. In the case of data concerning a grinding unit with 10 balls and the symmetrical raceway ($\alpha_A = \alpha_B = 0.785$ (45°)), the optimal dimensional rate of grinding is in both these cases, within the range of $Fr_P = 1.36 \div 1.60$. These calculations have been carried out with a friction index on steel and the internal friction of $\mu = 0.45$ and $\mu_w = 0.75$, respectively.

The author of [7] has put forward the assumption that grinding also occurs along some part of the raceway arc CB – Fig. 2. The active arc of grinding is determined by the simple model of the flow of the coal layer between the balls. The starting point of the active arc of the raceway results from the assumption that the peripheral speed of the given element of the layer must exceed the velocity of balls. The final point of this arc is determined by the external wrapping angle of the ball – α_B. The place at which the coal is dragged under the balls depends on the conditions of their influx on the raceway (the value and direction at the point A) and affects the shaping of the internal part of the rotating ring. In such a case, the optimal velocity of a unit consisting of ten balls, with a symmetrical raceway and horizontal shape of the internal part amounts to $Fr_P = 1.5$.

The presented models of the process of grinding are based on the assumption that the grinding material moves due to the effect of the following forces: gravity, centrifugal force and friction. Probably the particles are actually displaced partially by the body force and partially by being squeezed out from under the balls. The share of both these factors depends on the value of Fr and the mean angle of inclination of the raceway. In the case of low rates of grinding and a large inclination of the raceway (e. g. in the BM mills) the mechanism squeezing out is most decisive.

As it may be seen from what has been said above, the dimensionless velocity of the crushing ring amounts to $Fr_P = 1.3 \div 1.6$, i. e. it is lower than that of coal mills applied in Poland ($Fr_P = 1.9 \div 2.1$).

An important structural parameter of ring-ball mills is the unit thrust on the crushing surface, determined by the ratio of the total force P to the area of the cross-section of the grinding elements – $s_f = P/z_k \pi \rho_k^2$ [8]. From the viewpoint of disintegration, the formula (6) is more adequate, taking into account the diameter of the grinding elements (the balls) – $d_k = 2\rho_k$ and the length of the grinding line (the arc of the raceway) – $l_k = \rho_k(\alpha_A + \alpha_B)$

$$s_k = \frac{P}{d_k l_k z_k} = \frac{P}{2\rho_k^2(\alpha_A + \alpha_B)z_k} \tag{6}$$

At the wrapping angle of the ball $\alpha_A + \alpha_B = \pi/2$ both formulae are equivalent.

Investigations carried out on test stands [8, 12] indicated an increase of the efficiency of the mill affected by the growing thrust. The limiting values of the unit thrust, when the mill efficiency has not got an upward trend, may be as high as $s_k \geq 200$ kPa, probably due to the milling properties of the coal. In Polish ring-ball mills the applied nominal thrust amounts to $s_k \approx 125$ kPa. The values mentioned above are much lower than the limiting values.

3. Investigations on test stand

An experimental mill generally carries out the same process as an industrial mill. Three sets of ring-ball mills have been applied with diameter of the balls amounting to 125, 100 and 76 mm. All of them have nearly the same external diameters of $D_z \approx 427$ mm. The thrust on the balls is exerted by means of compression springs. The milling susceptibility of coal (grindability) which had to be ground was determined according to Hardgrove's method – $HGI = 60 \div 63$, the granulation amounting to $0 \div 7$ mm. The granular composition of the charged material was contained within the following ranges of mesh fractions: $R_{2.00} = 31.2 \div 37.4\%$, $R_{1.02} = 55.5 \div 63.2\%$, $R_{0.49} = 73.4 \div 80.0\%$, $R_{0.25} = 81.8 \div 90.4\%$, $R_{0.20} = 87.6 \div 93.8\%$, $R_{0.09} = 91.2 \div 96.1\%$, $R_{0.06} = 93.3 \div 98.0\%$.

The fundamental quantities characterizing the operation of the mill (without taking into account the wear of the grinding elements) are:

- maximum efficiency at a given granulation of the dust B^m,
- unit consumption of energy required for the grinding (without idle running) e,
- pressure drop in the mill Δp_m,
- flux of the drying and transportation gas (ventilation) V.

Quantities which facilitate the analysis of the mill work comprise:

- the thickness of the layer of material to be ground under the balls f_k,
- the pressure drop resulting from the presence of the solid phase in the milling chamber Δp_s.

A significant quantity concerning the operation of the mill is the number of circulation of the ground matter on its way from the grinding chamber to the sifter [1]. Its relative measure may be considered to be the drop of pressure due to the concentration of the ground matter along the section between the air-gap and the upper part of the grinding chamber (beyond the thrust ring). The resistance caused by the presence of the solid phase Δp_s may be calculated basing on the relation:

$$\Delta p_s = \Delta p_k - \Delta p_{sz} \tag{7}$$

where: Δp_k – total pressure drop in the grinding chamber,

Δp_{sz} – pressure drop brought about by the flow of gas alone.

The maximum efficiency of the mill B^m [4] is considered to be the flux of supplied coal, whose dust is characterized by the highest content of the finest class (e.g. $0 \div 0.09$ mm – $D_{0.09} \equiv D_{0.09}^{max}$ or $R_{0.09} \equiv R_{0.09}^{min}$) under the given conditions of exploitation. This quantity can be determined by changing the flux of drying and transportation gas (ventilation) V from its highest value to some permissible value resulting from the achieved minimum resistance of flow through the mill, without any change of the coal flux (the so-called "ventilation characteristic", i.e. $R_{0.09}$, e, Δp_m as functions of V – Fig. 3). In the experimental mill, additionally the thickness of the layer of matter ground under the balls f_k was measured, as well the total pressure drop over the height of the set of the grinding chamber Δp_k. The pressure drop Δp_s, brought about by the presence of the particles was calculated basing on Δp_k. Due to a further decrease of the gas flux, the mill undergoes restrictions of the maximum flow capacity (productivity) of the grinding unit. The granulation of the produced dust reaches the least value at the permissible ventilation V^{min} (corresponding to the lowest resistance).

Plotting these relations for various fluxes of coal we get pairs of points expressing the finest granulation of dust $D_x \equiv D_x^{max}$ or $R_x \equiv R_x^{min}$ (x – dust size) and the corresponding efficiencies $B \equiv B^m$, which are the main quantities of the so-called "universal characteristics". Basing on such a relation, we can determine the maximum efficiency of the mill at the given granulation of the dust.

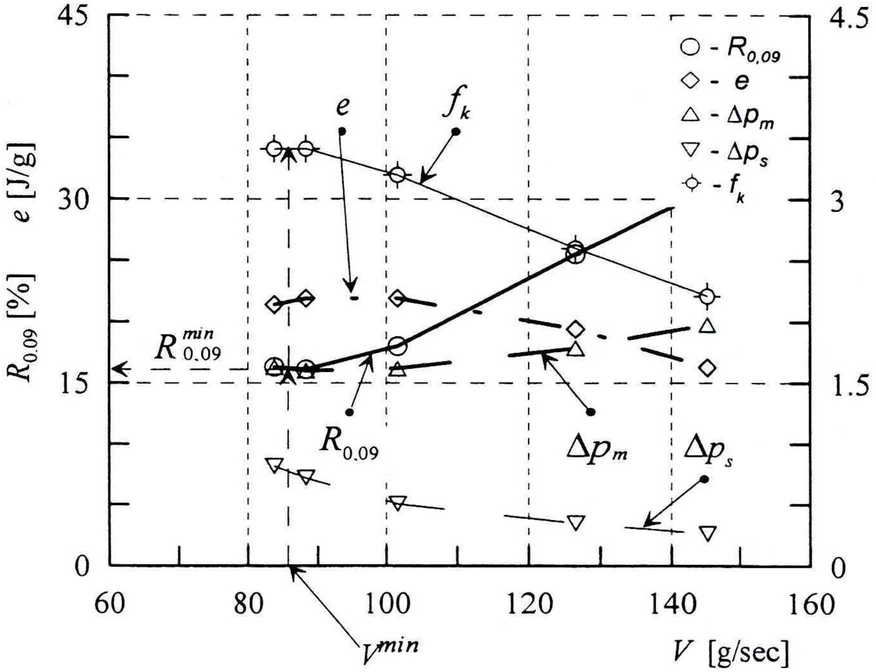

Fig. 3. Exemplary characteristics of ventilation of the experimental mill, i.e. $R_{0.09}$, e, f_k, Δp_m, Δp_s as functions of V, for: $z_k = 7$, $\omega = 10.5$ 1/sec, $P = 9.9$ kN, $B = 67.7$ g/sec

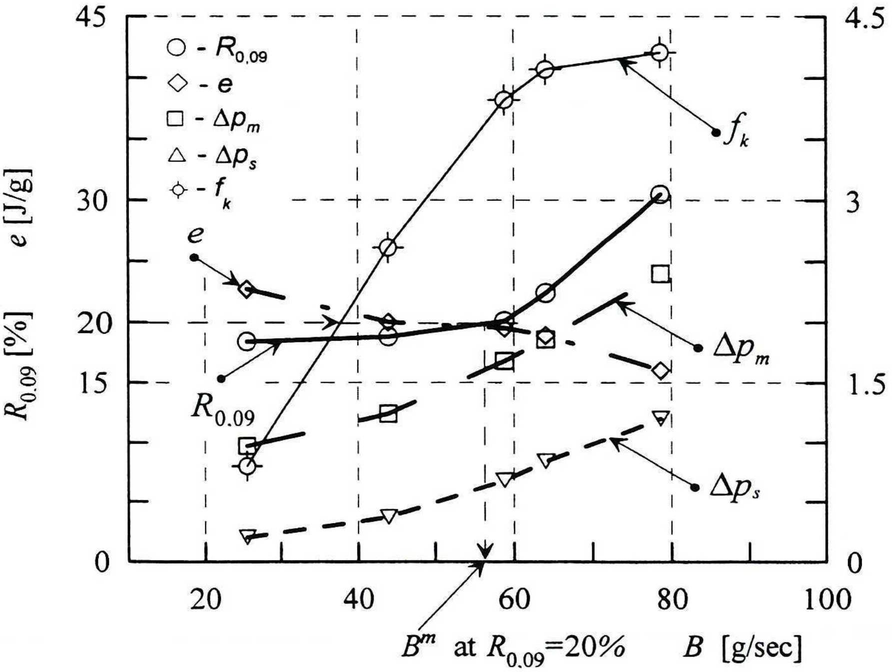

Fig. 4. Exemplary universal characteristics $R_{0.09}$, e, f_k, Δp_m, Δp_s as function of B for: $z_k = 7$, $\omega = 11.6$ 1/sec, $P = 6.6$ kN. For $R_{0.09} = 20\% - B^m \approx 58$ g/sec

In the present paper, the universal characteristics $R_{0.09}$, e, f_k, Δp_m, Δp_s as function of B have been determined at the same ventilation $V \approx 110$ g/sec (Fig. 4) in order to keep up approximately the same effect of screening on the process of milling. At the same position of the cyclone vanes, the flow capacity (the separation efficiency in its cumulative form) of the sifter depends mainly on the flux transporting the gas. The separation efficiency is defined as the dimensionless fluxes of the given class of particles of the outlet and inlet of the sifter. The second aim of drawing up the universal characteristics at constant ventilation was to compare the data with those quoted in [1]. From such a comparison, it results that the granulation of dust did not reach in the analyzed measurement its minimum, leading however to an inflexion due to the fact that the layer of the ground material reaches its maximum value. This probable minimum or inflexion of the relation $R_x(B)$ depends on the actual characteristics of the flow capacity (the separation efficiency) of the sifter.

The universal characteristics concerning the angular velocity $\omega \leq 12$ 1/sec are quantitatively similar to each other. The area of inclination of the relation $R_{0.09}(B)$ results from the essential limitation of the flow capacity of the milling elements, as it has been proved by the starting stabilization of the layer thickness under the balls f_k. To the right from the point of inclination of the curve the production of dust does not change much. A further increase of the load B, however, results in an excessive circulation of the ground material, a measure of which is the pressure drop over the height of the milling set, calculated for the solid component of the mixture (the milled material) Δp_s, as well as a deterioration of the screening process, which leads to a considerable coarsening of the dust.

In the case of the applied sifter and $V \approx 110$ g/sec in the area of the inflexion of the characteristics $R_{0.09}(B)$ (at various angular velocities ω), the granulation of dust amounted approximately to $R_{0.09} \approx 20\%$. Therefore, the efficiency of the mill was compared at a dust granulation of $R_{0.09} = 20\%$.

Investigations concerning the influence of the angular velocity and thrust were carried out on an experimental grinding set with seven balls (Fig. 5). In a comparatively wide area of angular velocity ($\omega = 9.5 \div 11.5$ 1/sec.) the value of $B^m(\omega)$ does not change much. This phenomenon is affected by the thickness of the layer under the balls, which decreases essentially with the increasing angular velocity. The energy consumption per unit in the process of grinding (without taking into account idle running) and the resistance of the flow rate undergo only inconsiderable changes.

An increase of the thrust enhances the maximum efficiency, shifting it towards a lower angular velocity. Under such conditions, a somewhat higher energy consumption per unit is observed. At comparatively high angular velocities ($\omega \geq 11.5$ 1/sec.), an increased thrust, exceeding the normal one does not cause any considerable increase of the efficiency (Fig. 5).

As the investigation has proved, the value of Fr_P corresponds to the determined thrust of the milling elements, due to the criterion of the highest effectivity of dust production in the mill.

The interdependence between the thrust and the angular velocity may be interpreted by describing the milling process, in which the active arc of the raceway changes with the velocity of the ring [7]. With the growing angular velocity, the thickness of the layer under the balls decreases considerably, which suggests that the active arc of the raceway is reduced. At the same time, the actual thrust per unit on the milled layer and the grinding effect (defined by the difference between the weight fraction of particles smaller than x (D_x) in the flux of coal B_m before and behind the raceway – Fig. 1) grows, reaching some limiting values [7]. Their further increase does not increase the efficiency of the mill. After a reduction of the angular velocity, due to the elongation of the active arc of milling, the thrust per unit drops below the limiting values. Under such conditions, their increase (exceeding the nominal values) results in an increased efficiency of the mill.

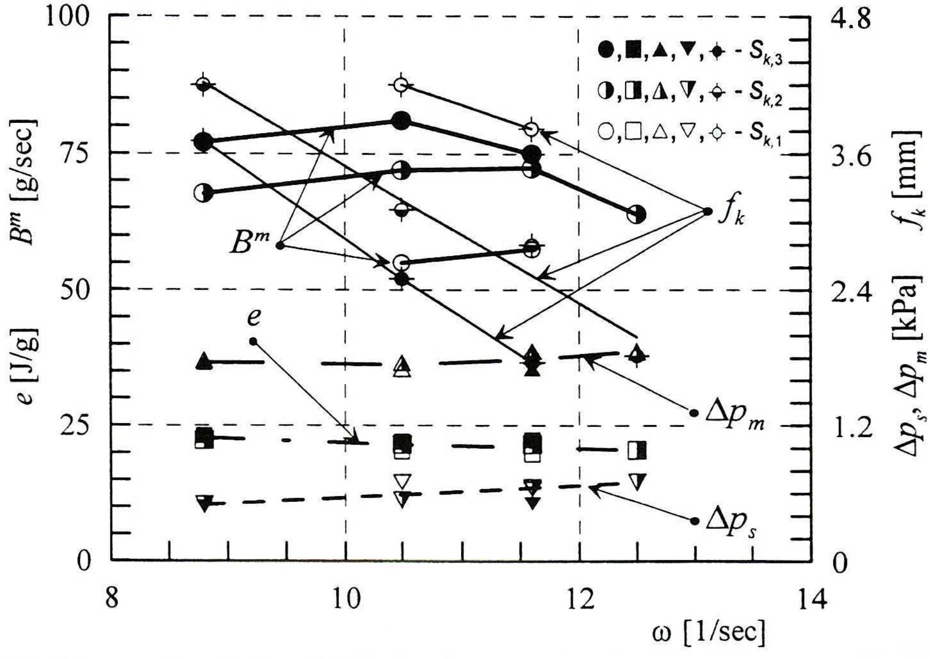

Fig. 5. The influence of velocity and thrust on the efficiency of a mill with seven balls for: $\alpha_A = \alpha_B = 45°$, $s_{k,1} = 77$ kPa, $s_{k,2} = 115$ kPa, $s_{k,3} = 154$ kPa

The results of investigations indicate that the velocity of the crushing ring can be lowered to $\omega \approx 9.5$ 1/sec. (or $Fr_P \approx 1.4$) without practically changing the maximum efficiency of the mill. The reduction of the mill velocity results in a decrease of the idle running energy and a reduced wear of grinding elements, and prolongs the lifetime of the power unit. These suggestions correspond to the partial operating data of 7M115-mill [3].

4. Result of industrial investigations

Theoretical analyses as well as investigations on the test stand have been partially verified in the mill EM-70 (Fig. 6). The milling set of this mill has nine 0.53 m diameter balls. They co-operate with a symmetrical crushing ring with a pitch diameter of $D_P = 1.575$ m and a total wrapping angle of the ball amounting to $\alpha_A + \alpha_B = \pi/2$. The thrust exerted on the balls is achieved by means of additional springs. In the course of measurements of this mill, three different thrust values were applied, i.e. $s_k = 104$, 125 (nominal) and 156 kPa as well as two angular velocities: $\omega = 5.08$ (nominal) and 3.96 1/sec. This corresponds to a change of the dimensionless velocity of $Fr_P = 2.07$ to $Fr_P = 1.26$.

The mill was equipped with an enlarged cyclone sifter adapted for fine grinding, as required by the applied technology of low-emission combustion. The position of the vanes at $\gamma = 35°$ has made it possible to achieve a dust granulation of $R_{0.09} \approx 20\%$.

At the nominal angular velocity of the mill $\omega = 5.08$ 1/sec, the achieved maximum efficiency amounts to $B^m = 3.17$ kg/s (11.4 t/h). The properties of the milled coal were as follows: net caloric value – 23.4 MJ/kg; ash content – 19.2%; moisture content – 8.0% and $HGI = 49$. The granulation of dust, determined on a screen with a mesh of 0.088 mm was $R_{0.09} \approx 20\%$. When the velocity was reduced to $\omega = 3.96$ 1/sec., the efficiency of the mill dropped to $B^m = 2.92$ kg/sec. (10.5 t/h), the characteristics of the milled coal remaining nearly the same. Measurements were carried out at a raised thrust per unit equal to $s_k = 156$ kPa. It ought to be mentioned that the achieved efficiencies were restricted by the possibility of the assumed transporting dry gas flux, due to the rather low compression of the fan.

When a mill with a reduced rotational speed within the range $B < B^m$ was applied, the obtained dust was somewhat finer, in spite of applying the same ventilation and adjustment of the regulation element of the sifter. In the range of medium efficiencies, a motor with a lower rotational speed consumes less electric energy (among others due to the reduction of idle running energy). However, in the case of higher loads, the consumed power rating increased faster in relation to its changes in a standard motor.

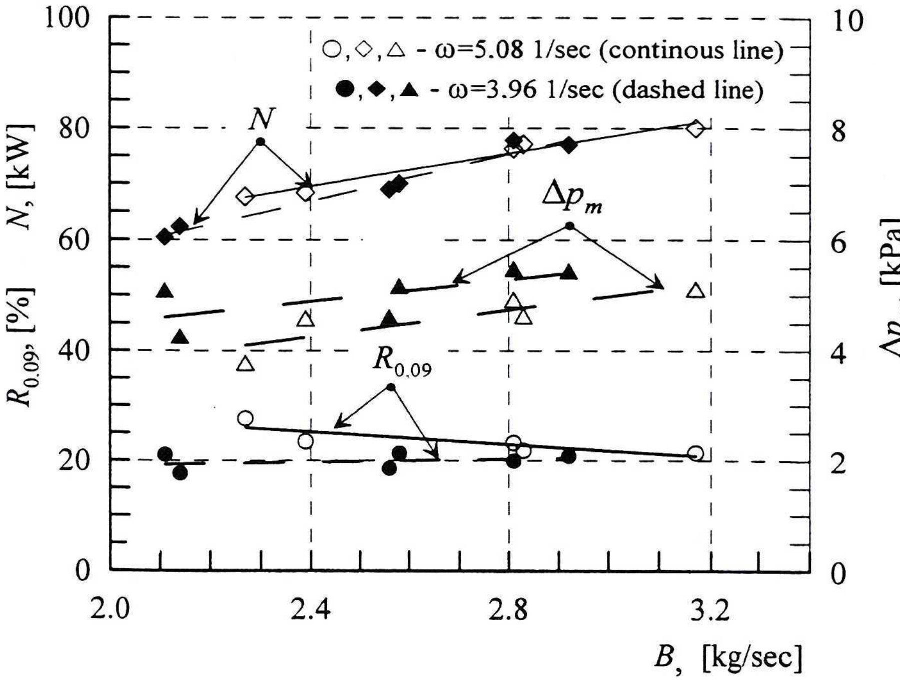

Fig. 6. The angular velocity effect on the performance of EM-70 mill

An increased thrust of the springs resulted practically in a linear increase of the efficiency of the mill. The adjustment of the regulation elements of the sifter remaining unchanged, the maximum efficiency of the mill grew from 2.72 kg/sec (9.8 t/h) to 3.17 kg/sec (11.4 t/h), while the thrust per unit s_k was changed from 104 kPa to 156 kPa. The energy consumption per unit of grinding amounted in both cases to about 25 J/g.

Comparative measurements of the EM-70 mill and after its modernization were made, as well. In the new mill, the current grinding set consisting of nine balls was replaced by a six-balls unit with 0.75 m diameter. In both cases, the pitch diameter of the crushing ring was the same. For the comparable granulation of dust ($R_{0.09} \approx 30\%$), the efficiency of this new mill grows by about 30%.

5. Conclusions

When we choose the geometry of the milling unit, the idea of applying only few balls with a larger diameter is most adequate. This concerns mainly reconstructed mills of the type EM-70, in which the grinding sets consisting of nine balls are replaced by six-ball units. If one applies the same driving unit (power unit), the efficiency of this new mill increases by about 30%.

Investigations carried out on an experimental test stand have shown that the maximum efficiency of the mill does not change much in a wider range of angular velocities $\omega = 9.5 \div 11.5$ 1/sec. ($Fr_P = 1.4 \div 2.0$). These data have also been confirmed by measurements of an EM70 mill. A reduction of the angular velocity by 22% with respect to the nominal one, caused a reduction of the efficiency by about 8%.

It would be expedient to reduce the rotational speed of the mills used in Poland to the value of $Fr_P = 1.4 \div 1.6$. The possible abatement of the efficiency might be compensated by an adequate thrust of the balls. A decreased rate of milling will reduce the level of vibrations and prolong the lifetime of the respective elements in spite of the increased thrust of the balls, as has been proved by partial experiments in situ.

Basing on data quoted in literature and on experimental investigations the proper thrust on the milling elements depends on the breakage properties of the coal. In some installations processing dust, in the case of restricted capacities of milling, an increased thrust can raise successfully the maximum efficiency of the mills. However, this ought to be preceded by an adequate controlling test.

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Dobór cech konstrukcyjnych młyna pierścieniowo-kulowego

Streszczenie

W artykule przedstawiono sposób doboru cech konstrukcyjnych (geometrii, prędkości mielenia, nacisku) młynów pierścieniowo-kulowych. Porównano różne metody obliczeń optymalnej prędkości mielenia. Na podstawie badań eksperymentalnych, pilotowych i przemysłowych, zweryfikowano wpływ prędkości kątowej i docisku kul na wydajność młyna. Wyjaśniono współzależność prędkość mielenia – nacisk elementów mielących. Zalecono zmniejszenie prędkości obrotowej zespołu napędowego dla poprawy cech eksploatacyjnych młyna.