BALL MILL POWER CALCULATION WITH INCLINED PARTITION
Vasily S. Bogdanov, Yuri M. Fadin, Svetlana Yu. Lozovaya, Sergey S. Latyshev, Nikita E. Bogdanov, Olga S. Vasilenko
Russia, 308012, Belgorod, Kostyukova.

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Abstract

In order to improve the efficiency of tube open cycle ball mills, particularly for a clinker and additive grinding the mills with transverse longitudinal movement of the grinding elements were proposed. In these mills, the vertical interchamber partition is replaced by a sloped interchamber partition. At that the grinding elements start to make not only a cross, but also a complex longitudinal movement. At that the work of grinding bodies is intensified. The existing methods of consumed power calculation cannot be used, since the level of grinding media in the chambers, and the required mass centers change from a minimum to a maximum value by turning a mill by 180°, and this happens all the time. The drive power changes. The methods of power consumption calculation are developed for a tube mill with cross-longitudinal motion of the grinding elements, which takes into account the capacity of the mill with a vertical partition. The power is added to it spent on transverse longitudinal movements of the grinding elements, and the power is taken away which is released at the expense of grinding body weight crushing in a mill. According to the proposed method the calculation of power consumption was performed for the tubular ball mill Ø4x13,5 m. They also recorded the consumed power values concerning a similar mill at the Karachay-Cherkessia cement plant. The error made 3%. This error is much more significant among the existing Tovarov's and Bond-Rowland's techniques, i.e. the developed method can be proposed for the calculation of the mill drive power with transverse longitudinal movement of the grinding bodies.

Keywords: Tube ball mill, cross-longitudinal movement, interchamber inclined partition, interchamber vertical partition, chamber length, loading ratio, power, natural slope angle, grinding bodies, milling.

Introduction: The annual volume of cement production in the world makes more than 3.5 billion tons. More than 85% of cement is produced by dry method. The specific energy consumption makes 80 - 120 kWh/t.
At more than 75% of energy is consumed for crushing: the crushing and grinding of raw materials, the grinding of a clinker and additives, coal grinding.

The most energy-intensive process is the clinker and additive grinding. 40-45 kWh/t of energy is spent for it. Various designs of mills are used for clinker and additive grinding: ball drum (BDM), disc-roller or vertical mills (VM), horizontal mills (HM), roller-pendulum, ball ring, press roll mills (PRM), vibratory and aerodynamic ones.

Despite the variety of used mill designs, the ball drum mills were the most popular ones - 85%.

Regardless of a mill design the grinding of material in them is performed by blows, crushing and abrasion. The calculations and experimental studies indicate that no more than 5% of the supplied energy is used directly for crushing (the decrease of material particle size) and the rest of the energy is converted into heat and sound one and into the overcoming of losses in mechanical transmissions [1,2,3,4,5].

In Russia, about 70% of all BDM operate in an open cycle. It is impossible to change the grinding schemes for all mills, so it is important to increase the effectiveness of the mills with an open grinding cycle.

Main part

A distinctive feature of the tube mills operation equipped with inclined interchamber partitions (IIP), is that during each turn of a drum the grinding bodies move not only in cross-section but also along the axis of mill rotation. At that the level of grinding bodies in the chambers, and, consequently, the position of mass load center varies from minimum to maximum one, which in its turn causes the change of consumed power amount. For example, the loading level in a mill of 4x13,5 m equipped with IIP set at the angle of 45° varies from 0.6 to 1.2 m at each drum turn, and the consumed power of the drive makes 2680 - 2450 kW respectively.

During the operation of the tube mills with vertical partitions (VP) the chamber length and the position mass load center does not change. The consumed drive power also remains unchanged. It is known that the performance of the mills with VP is proportional to the consumed power and the weight of grinding bodies. The results of laboratory studies, the experience of commercial operation and the performed calculations showed that the power consumed by IIP mill, at the same load weight is higher than among the mills with VP. It was found that the amount of power consumed by IIP mill is significantly influenced not only by the mass of the grinding bodies, the chamber length, the angle of a partition inclination, but also the angle of a load slope [6-13].

The industrial studies of tube mills with various sizes (2,6x13; 3x14; 3,2x15; 4x13,5 m) equipped with IIP showed that during mass load decrease, especially in the first chamber, their performance is not only reduced, but also
increased, which contradicts existing theories and requires clarifications. For example, the mass of grinding bodies along the mill chamber of 3.2x15 m with VP makes 60 and 80 t, respectively, the capacity makes 49 t/h, and the consumed power makes 1680 kW. The specific output per weight unit of the grinding bodies makes 0.350 kg/kg, including: spheres - 0.82 kg/kg, cylpebs - 0.61 kg/kg. After the change of VP into IIP ([beta] = 45°) in a mill the weight of grinding bodies along the chambers was reduced to 30 and 60 tonnes respectively, i.e. by 50 tonnes. At that, the performance increased to 56 t/h, and the power consumption reduced to 1420 kW. The specific output of milling body weight per unit made 0.622 kg/kg, balls - 1.86 kg/kg, cylpebs - 0.93 kg/kg. Thus, the efficiency of grinding element operation in a mill at the replacement of VP into IIP increased by 1.77 times, the efficiency of balls increased by 2.26 times and the efficiency of cylpebs increased by 1.52 times. This is explained by the greater longitudinal mobility (smaller angle of natural slope) of grinding bodies with a circular shape as compared with a cylindrical one (cylpebs). The replacement of cylpebs in the second chamber among the mills, equipped with IIP small balls (15-30 mm in diameter), will significantly increase their productivity. This was confirmed by laboratory tests. With the reduction of the grinding body mass the loads on a drum, pins, bearings, gear, motor are reduced and the operational reliability and IIP mill utilization ratio is increased. For example, 4x13.5 m mill utilization rate at Karachay-Cherkessia cement plant increased from 0.74 to 0.87. This allowed to produce 30 thousand tons of cement additionally.

Energy savings exceeded 1.5 mln. kWh and the savings of grinding bodies made 250 tons per year.

An achieved positive effect of the inclined wall use and the rapid paces of their implementation necessitate the necessity of technique development that would allow to calculate the power consumption, taking into account such important factors as the angle of a wall tilt, the angle of the grinding bodies natural slope, the length of the chambers, the drum speed and load factor.

The existing techniques [14,15] can not be applied because they do not take into account the factors of the grinding body longitudinal motion, the presence of an inclined wall, the change of load mass center position and the natural slope angle of the grinding bodies. Their practical use is impossible due to their large surfaces. The basis of the proposed calculation method is the assumption that the an inclined wall interchamber consumes the additional power to change the loading mass center position in a vertical plane and to overcome the friction forces at the horizontal movement of the grinding bodies. Let's calculate the power needed to move the milling bodies 4 of the sloping wall 2 using the example of a coarse grinding chamber I (Fig. 1).
Fig. 1. The designed diagram of a cement mill with oblique interchamber partition: 1 - coarse grinding chamber; 2 - interchamber sloping partition; 3 - fine grinding chamber; 4 - grinding bodies; 1,2 - specific positions of a sloping wall; l1,l2 - the lengths of coarse grinding chamber I and fine grinding chamber 3 respectively; R - mill radius; h - the level of grinding body loading.

The coordinates $X_c, Y_c, Z_c$ of loading mass center $C$ in the first chamber:

$$
X_c = V^{-1} \iiint_{V} x \, dx \, dy \, dz;
$$

$$
Y_c = V^{-1} \iiint_{V} y \, dx \, dy \, dz;
$$

$$
Z_c = V^{-1} \iiint_{V} z \, dx \, dy \, dz,
$$

where $V$ is the volume occupied by the load. The volume occupied by the load is limited by the surfaces of a sloping wall and a mill drum, a front bottom and the level of grinding bodies, which are respectively described by the equations:

$$
\begin{align*}
X \sin \xi - (y - l) \tan \beta + z \cos \xi &= 0; \\
Y &= 0; Z = -(R - h),
\end{align*}
$$

where $R$ - the radius of a drum and a mill in the light; $l$ - the distance from a front bottom to an IIP along the axis of a drum; $[\beta]$- the angle of a partition inclination; $[\chi]$- IIP (drum) rotation angle; $h$ - the load level in a chamber.

The load level $h$ is the function of $[\chi], l, [\beta], [\phi]$:

$$
0.5 \pi - \arcsin X - X(1 - X^2)^{1/2} = \pi \phi + 2 \cos \xi (3 \tan \beta)^{-1}(1 - X^2)^{1/2}
$$

The unlimited parameters are introduced in (4) to simplify calculations:

$$
X = (R - h) R^{-1}; \lambda = l R^{-1}.
$$
After the calculation of the integrals (2) by the volume bounded with the surface (2), and the use for transformations (3) we shall obtain the coordinates of the mass center:

\[ L_{\mu} = \pi \sin \xi (4t \beta)^{-1} \varphi + \sin \xi \cdot (6b \beta)^{-1} (\cos \xi - bx)(1 - x^2)^{\frac{3}{2}}; \]
\[ L_{\nu} = (1 + 4b^2) \pi \rho (8t g^2 \beta)^{-1} + 12b \beta^2 (\cos \xi - bx - 4b \cos \xi) \cdot (b - x \cos \xi))(1 - x^2)^{\frac{3}{2}}; \]
\[ L_{Z} = \pi \cos \xi (4t \beta)^{-1} \varphi + (6b \beta)^{-1} (\cos \xi (\cos \xi - bx) - 4b(b - x \cos \xi))(1 - x^2)^{\frac{3}{2}}; \]
\[ L_{X} = \frac{V_{xc}}{R^4}; L_{Y} = \frac{V_{yc}}{R^4}; L_{Z} = \frac{V_{zc}}{R^4}; b = \lambda t \beta. \]

The work spent for the load rise to the height \( \Delta Z_c \),

\[ A_b = G \Delta Z_c = g\gamma N \Delta Z_c, \]

where \([\text{gamma}]\) is the load density. Thus, the power spent on the load rise is the following one:

\[ N_{b} = g\gamma N \cdot dz_c /dt = g\gamma R^4 \cdot dL_Z /dt. \]

By moving the center of load mass in a horizontal plane (along the axis X and Y) the load weight force does not perform an additional work. However, in this case, an additional work is performed to overcome the forces of load friction on the inner surface of a drum:

\[ A_{TP} F_{TP} S = fGS, \]

where \( f \) - sliding friction ratio; \( S \) - the movement of loading mass center in a horizontal plane.

The additional consumption of power to overcome friction forces

\[ N_{TP} = fg\gamma N \cdot dS /dt. \]

Taking into account that \( V=\text{const} \), and \( dS^2 = dx^2 + dy^2 \), then

\[ N_{TP} = f g\gamma R^4 ((dL_X /dt)^2 + (dL_Y /dt)^2)^{\frac{1}{2}}. \]

On the basis of (6), the derivatives \( dL_X /dt, dL_Y /dt, dL_Z /dt \) are equal to:

\[ dL_X /dt = V_x = \omega \cos \xi (4t \beta)^{-1} (\pi \rho + 2(1 - x^2)^{\frac{3}{2}}(3b)^{-1} \times (\cos \xi - bx - 4b(1 - x)^2 \sin \xi (3 \cos \xi (b - x \cos \xi))^{-1}); \]
\[ dL_Y /dt = V_y = \omega \sin \xi (1 - x^2)^{\frac{3}{2}} (3t g^2 \beta)^{-1} (b - x \cos \xi - (1 - x^2) \sin \xi (3(b - b \cos \xi))^{-1}); \]
\[ dL_Z /dt = V_z = \omega \sin \xi (4t \beta)^{-1} (-\pi \rho + 2(1 - x^2)^{\frac{3}{2}}(b \cos \xi (3b)^{-1}). \]
where $\omega$ is the angular speed of drum rotation.

Total power consumption $N_1$ for the movement of the grinding bodies in a single mill chamber with IIP:

$$N_1 = N_b + N_{ip} = g\gamma R^4 (V_z + f(V_x^2 + V_y^2)\frac{1}{2}).$$ (13)

In order to calculate the consumed power for the movement of the grinding bodies in the second chamber within the formulae (1) - (13) it is necessary to replace $\chi$ by $\pi + \chi$ and $\omega$ by $\omega$ and use the second chamber characteristics: $\lambda_2$ and $\phi_2$. Then the total additionally consumed power of the mill further with IIP is calculated as follows:

$$N_a + N_1 + N_2.$$ (14)

The observations of the laboratory device operation with a transparent drum and the study results of the industrial mills indicate that IIP makes an impact on the work nature concerning the part of the load, which is located in the zone of its active influence and is conditionally limited by $l_p$ radius of the influence zone, which, in its turn, depends on the angle of E load natural slope. It was found that the smaller the angle of the load natural slope, the higher its longitudinal mobility, the greater the weight of grinding bodies leaking under the inclined partition and moving by it, the greater the power consumption and vice-versa. Thus, if we introduce the relative radius of an influence zone into (2)-(6) instead of chamber length $l$, which is dependent on $\beta$, $\phi$, $\epsilon$, and is equal to

$$\lambda_p = l_p/R = (tg\beta - tg\epsilon)(2tg\beta \cdot tg\epsilon)^{-1}(z_a - z_c).$$ (15)

then (14) will take into account all the factors influencing the additional mill power consumption with a longitudinal-transversal load movement. In (16) $Z_a$ and $Z_i$ are two different roots of the equation

$$1.5z(z(1 - z^2)^{\frac{1}{2}} + \arcsin z + \pi(0.5 - \varphi)) + (1 - z^2)^{\frac{3}{2}} -$$

$$-tg\beta(tg\beta - tge)(1 - x_c^2)^{\frac{3}{2}} = 0,$$ (16)

where $X_c$ – an average relative load level, $X_c = 0.832 - 1.68[\phi]$.

The total power consumed by the mill with cross-longitudinal load movement,

$$N = N_0 - \Delta N_0 + N_n,$$ (17)

where $N_0$ is the power consumed by the mill with VP under the existing $[\phi_0$ - the power released by reducing the body weight at the replacement of VP into IIP; $N_n$ additionally consumed power for the movement of grinding elements with an angled plate.
The released power magnitude $\Delta N_\varphi$ at the load decrease from $[fi_0]$ to $[fi]$ may be calculated according to one of the following formulae:

$$\Delta N_{\varphi}^T = N_0 - A_i \varphi^4; \quad \Delta N_{\varphi}^0 = N_0 - A_0 (\varphi + 0.1);$$

(18)

$$\Delta N_{\varphi}^{tp} = N_0 - A_{tp} \cdot \varphi(1.07 - \varphi).$$

(19)

where AT, A0, the power coefficients obtained from the power calculation formulas Tovarov's, Olevsky's, Bond-Rowland's calculation formulas.

Power factors at original $[fi_0]$ and No:

$$A^T = N_0 / \varphi_0^4; \quad A^0 = N_0 / (\varphi_0 + 0.4); \quad A^{tp} = N_0 / (\varphi_0(1.07 - \varphi_0)).$$

For example, for the mill of 4x13.5 m at $[fi_0]=0.3$ and $N_0=3200$ kW; $A_T=8253$ kW; $A_0=7875$ kW; $A_{BR}=13636$ kW [15]. Thus, at the replacement of VP into IIP in a mill it is necessary to calculate the power consumption $N_n$, first of all and then the released $\Delta N_\varphi$ taking into account the load mass decrease.

The installation of an inclined partition without the change of grinding body weight can result in an emergency shutdown of a motor. For example, the maximum power consumption for the mill of 4x13.5 m makes 680 kW, which is 21% higher than the installation drive power.

At the replacement of a vertical wall into a sloping one without changing the installed power of a drive it is necessary to determine the maximum possible load factor of chambers, in which the released power $\Delta N_\varphi$ will be equal to additionally consumed one, i.e. $\Delta N_\varphi = N_n$. For example, Fig. 1 represents the dependencies $N_n$ and $\Delta N_\varphi$ on $[fi]$ for the mill of 4x13.5 m, calculated on the basis of proposed methods. The projection of the intersection point $N_n^{max}$ and $\Delta N_{\varphi}^T$ the coordinate $\varphi$ shows, that the maximum load factor of the mill chambers at a partition inclination angle of 50° makes 0.264.

At that the maximum values of released and additionally consumed power $\Delta N_{\varphi}^T = N_n^{max}=316$ kW. The average additionally consumed power at $[fi] = 0.264$ makes about 216 kW, i.e. 100 kW less than the released one. Fig. 2.26 shows the change of additionally consumed power in a single rotation of a drum at the partition inclination angle equal to 50°. The change of power consumed by the mill with a sloping partition is sinusoidal one and varies (for the mills of 4x13.5 m) from 50 to 410 kW.
At that, its maximum corresponds to $\chi = 280^\circ$, i.e. to such state of a partition, at which it scoops the grinding bodies at the site, $\alpha \delta$ and goes from the position II into the position I, raises them to the maximum height and resets the position I corresponds to the position $[\chi]=0$.

The minimum value corresponds to the position II of the partition when $N_b=0$ and the power is consumed additionally only to overcome the friction forces at the longitudinal movement of the grinding bodies under the partition. And when $[\chi]=0...1800$ $N_b < 0$, i.e. the nature of grinding body work in this movement range contributes to the transfer of the energy to a drum an additional torque is created, whereby additionally consumed power is reduced further by 155 kW. According to Fig. 2 the work performed to overcome the friction forces on the longitudinal movement of the grinding bodies is 47% more than the work for their raise.

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**Figure 2. Determination of the limit load factor and the value of consumed power reduction at the replacement of the vertical partition into the inclined one**

$[\psi]=0.76$; $[\chi]=8^\circ$; $f_{tr}=0.4$

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**Fig. 3. The dependence of additional power consumption on the angle of a mill drum rotation.**
Consequently, at the same mill productivity the weight of grinding bodies, due to the intensification of their movement, can be reduced by more than a certain value according to the maximum allowable load factor, i.e. to 47%.

However, a significant decrease of grinding body weight reduces the grinding efficiency by crushing, and despite the additional grinding of material by abrasion (due to the longitudinal movement of the grinding bodies), the grinding is roughened in general.

The performance of 4x13.5 mill with a vertical and a sloped partition makes 85 t/s. At that the mass of the grinding bodies is reduced from 230 to 165 tonnes (by 39%), and the consumed power is reduced from 3170 to 2520 kW. The subsequent reduction of grinding body mass down to 120 m leads to the grind roughening. The residue on the sieve 008 is increased from 9 to 15%.

A great influence on the consumed power and the efficiency of the grinding process is performed by the natural slope angle of the grinding bodies (Fig. 4). At the decrease of E the consumed power and performance increase, as the longitudinal loading mobility is also increased. The grinding bodies of a large diameter have a larger angle of natural slope, and vice versa. In an industrial environment the loading of mill chambers with inclined partitions should have a smaller average weighted diameter of a ball. For example, at the weighted average

![Diagram](image-url)

**Fig. 4. The influence of a natural slope angle on additionally consumed power.**

\[
[f_i_1] = [f_i_2] = 0.30; \quad f_{rp} = 0.40; \quad [\lambda] = 2.63
\]

Diameter of 60 mm ball, the 45 t load weight of the first chamber the consumed power of the mill 4x13.5 m 2450 kW, the production rate 80 t/h; at an average weighted diameter of 48 mm ball the capacity increased to 85 t/h, and the consumed power increased up to 2520 kW.
With the change of E from 20 to 2° the additionally consumed power increases from 280 to 600 kW (Figure 3).

Industrially, a natural slope angle of the grinding bodies in the mill make 5-20° without the material, with the material (clinker) of 15-40° and it depends as on the average weighted diameter of a ball, like lining type, and on the type and the fractional composition of the crushed material. On the basis of (17) the total capacity of the mill 4x13,5 m at \([\text{fi}] = 0.235; [\text{Beta}] = 50 \, ^\circ; E = 15 \, ^\circ\) and the weight of milling bodies equal to 165 tons makes 2680 kW, and the measured power makes 2600 kW. The error makes about 3%. The power calculated by Tovarov makes 2780 kW, the power calculated by Bond-Rowland makes 2865 kW.

Summary

The basis of the proposed methodology for the calculation of power consumption by tubular ball mill with the cross-longitudinal motion of grinding bodies is the assumption that an inclined interchamber partition consumes additional power to change the load mass center position in the vertical plane and the extension of friction forces at the horizontal movement of the grinding bodies.

Conclusions

The power calculation formulae of a mill cited in this article with the cross-longitudinal motion of the grinding elements is adapted to the structures of industrial mills, the error makes 3%.

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References


