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CALCULATION OF THE POWER DRAW OF DRY MULTI–COMPARTMENT BALL MILLS

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In this paper, a new approach for the calculation of the power draw of cement grinding ball mills is proposed. For this purpose, cement grinding circuit data including the operational and design parameters were collected from 14 industrial ball mills, ranging in diameters from 3.2 to 4.8 m. The ball loads within the mills were measured by different methods proposed in the literature and power draw of each mill were calculated. The results showed that power draw of the cement mills could accurately be predicted by the method proposed in this study.

Key words: power draw, cement, dry grinding, ball mill

INTRODUCTION

Energy is the most important cost item in a cement plant. About 60% of the electricity consumption for cement production is used for grinding the raw material and cement clinker (Zhang et. al., 1988). Annual cement production is approximately 1.6 billion tons and the grinding process consumes nearly 2% of the electricity produced in the whole world (Norholm, 1995).

Grinding of cement clinker has been traditionally performed by the ball mills which can either be open circuit or closed circuit with an air classifier. Selection of right mill for the specified duty is the most critical for circuit design, since it has the highest capital and operating costs.

Bond method has been used for ball mill selection in both mineral and cement industry for 50 years. It is basically rely on determination of grindability of material in a specified laboratory mill. Then, using empirical equations developed by Bond, and later with minor revisions by Rowland, the mill size is determined (Rowland, 1985; Napier-Munn et. al., 1996; Man, 2000). Once, the size and ball load is determined, the power draw for a given mill is calculated using Equation 1.

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$$KW_b = 4.879 \times D^{0.3} \times \left(3.2 - 3V_p\right) \times fC_s \times \left(1 - \frac{0.1}{2^{9-10C_s}}\right) + S_s \tag{1}$$

where

Kwb – Kilowatts per metric ton of balls
D – Mill diameter inside liners in meters
V_p – Fraction of mill volume loaded with balls
fC_s – Fraction of critical speed
S_s – Ball size factor

To determine the power that a dry grinding needs, full grate discharge mill Equation 1 is multiplied by the factor of 1.08. A multi-compartment ball mill consists of two or more grate discharge ball mills in series. The same equation is used to calculate the power that each ball mill compartment should draw. The total power is the sum of the power calculated for each of the separate compartments.

Although, Bond's method has been widely used, the required link to classification is missing. Therefore, it is not possible to calculate circuit performance when any of the design and operational parameters are changed (Napier-Munn et. al., 1996; Man, 2000). Model based methods has becoming popular to overcome these deficiencies (Herbst and Fuerstenau, 1980; Austin and Klimpel, 1982; Kavetsky and Whiten, 1982; Morrell and Man, 1997).

Morrell and Man (1997) proposed a model based approach using the results of the Bond ball mill grindability test for overflow wet ball mills. An approach was proposed by Erdem (2002) for dry multi-component cement grinding ball mills, using the results of the Bond ball mill grindability test.

For all model based methods, a reliable method to calculate mill power draw for a given mill is required for the calculation of power draw. Morrell (1996) proposed a mathematical model for autogenous, semi-autogenous and ball mills which is based on the motion of grinding charge inside the mill. He also verified his approach with various plant data (Napier-Munn et. al., 1996).

In this study, power draw of 14 multi-compartment cement grinding mills were calculated based on Morrell's approach. Design and operational parameters for the mills were collected from operating plants. With this respect, ball load within the mill which is the most determining factor for power draw was determined by several methods proposed in the literature (Austin et. al., 1984; Napier-Munn et. al., 1996).

MORRELL'S C-MODEL (1996)

The charge is treated as a continuum, which allows analytical solutions to the equations that are developed. The model can be expressed as:

$$\text{Gross power} = \text{no-load power} + (k \times \text{charge-motion power}) \tag{2}$$

Where gross power is the power input to the motor, no-load power is the power input to the motor when the mill is empty, charge-motion power is the power associated with the movement of the charge, and (k x charge-motion power) is the total power input to the charge. k is a lumped parameter that allows for heat losses and energy consumed. In this model, there are three principal equations for calculating the power draws associated with the charge in the cylindrical and conical end-sections of a wet tumbling mills. Power draw of cylindrical section is calculated using Equation 3, Power draw of conical section is calculated using Equation 4, and no-load power is calculated using Equation 5 (Morrell, 1996). Schematic diagram of cone-end of a wet system ball mill seen in Figure 1 is not so same shape as the dry system multi-compartment ball mill. This area covers too small place of all grinding surface due to design form, so power draw of conical section is negligible when calculating the gross power of tube mills.

$$P_t = \left[\frac{\pi \cdot g \cdot L \cdot N_m \cdot r_m}{3(r_m - z \cdot r_i)}\right] \times \left[2r_m^3 - 3z \cdot r_m^2 \cdot r_i + r_i^3(3z-2)\right] \times \left[\rho_c \cdot (\sin\theta_S - \sin\theta_T) + \rho_p \cdot (\sin\theta_T - \sin\theta_{TO})\right] + \left[L \cdot \rho_c \cdot \left(\frac{N_m \cdot r_m \cdot \pi}{(r_m - z \cdot r_i)}\right)^3 \times \left[(r_m - z \cdot r_i)^4 - r_i^4 \cdot (z-1)^4\right]\right] \tag{3}$$

$$P_C = \left[\frac{\pi \cdot g \cdot L_d \cdot N_m}{3(r_m - r_t)} \times \left[r_m^4 - 4r_m \cdot r_i^3 + 3r_i^4\right]\right] \times \left[\rho_c(\sin\theta_S - \sin\theta_T) + \rho_p(\sin\theta_T - \sin\theta_{TO})\right] + \left[\frac{2\pi^3 \cdot N_m^3 \cdot L_d \cdot \rho_c}{5(r_m - r_t)} \times (r_m^5 - 5r_m \cdot r_i^4 + 4r_i^5)\right] \tag{4}$$

$$p_y = 1.68 \cdot D^{2.05} \times \left[\phi \cdot (0.667 \cdot L_d + L)\right]^{0.82} \tag{5}$$

P_t – Power draw of cylindrical section, kW
P_c – Power draw of conical section, kW
L – Length of cylindrical section of mill inside liners, m
L_d – Length of cone-end, m
N_m – Rotational rate of mill, rev/s
g – Acceleration due to gravity, m/s^2
ρ_c – Density of total charge, t/m^3
ρ_p – Density of discharge, t/m^3
Z – Parameter
D – Diameter of cylindrical section of mill inside liners, m
r_m – Radius of mill inside liners, m
r_i – Radial location of inner surface of charge, m
r_t – Radius of discharge trunnion, m

ϕ – Fraction of theoretical critical speed, %
θ_S – Angular displacement of shoulder location at mill shell, radians
θ_T – Angular displacement of toe location at mill shell, radians
θ_{TO} – Angular displacement of surface of slurry pool at toe, radians

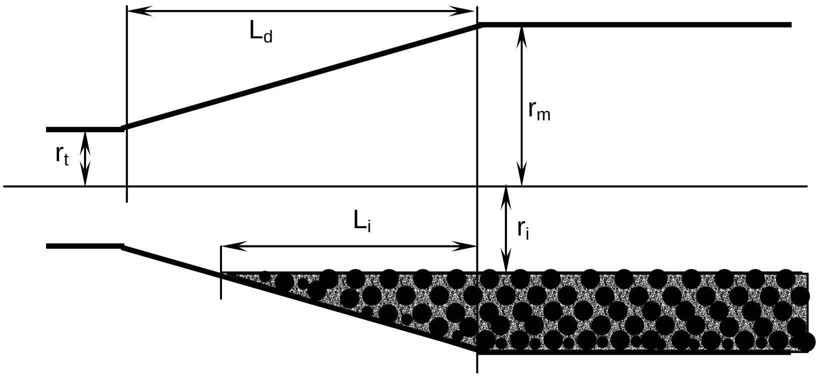


Figure 1. Schematic diagram of cone-end of a wet system ball mill

EXPERIMENTAL WORK

To verify the new power draw approach, detailed surveys of the 14 ball mill circuits at 6 different plants were carried out. The ball mills sampled in this study are ranging in diameters from 3.2 m to 4.8 m. Design and operational parameters of the ball mills sampled are given in Table 1.

Table 1. Sampled ball mill's design and operational parameters range

Operating and Design Variables	Values
Mill diameter	3.2 – 4.8 m
1st chamber length	3.15 – 4.25 m
2nd chamber length	5.18 – 10.00 m
Total fractional mill filling of 1st chamber length	29.00 – 32.98 %
Total fractional mill filling of 2nd chamber length	27.20 – 34.90 %
Mill rotational speed	14.87 – 17.34 rev/min
Fraction critical speed	71.89 – 77.02 %
Specific gravity of ore	2.90 – 3.10 tons/m^3
Bulk density of ore	1.54 – 2.07 tons/m^3
Mill Power	1450 – 5200 kW

The mill load that is the volume of charge in the mill is the principal determinant of power draw. Estimation of the ball load that is mixed with the cement charge is difficult and can be highly erroneous. So direct measurement must be taken for calculation of mill load. A direct measurement of the load entails the crash stopping of the ball mill under load whilst the mill is running under steady state conditions. Before taking measurement steady state conditions were verified by the plant staff, then the mills were crash stopped so that required measurements could be taken from the both compartments along the grinding path inside the mills. The load within the mills was determined by measuring the width and length of the charge and perpendicular distance between the charge and liner surface at various points in each compartment as seen in Figure 2. At the same time, all variables measured were recorded in the control room during these operations.

From these measurements the load volume can be calculated with using simple geometry and different equation proposed by Morrell and Allis Chalmers Company. Mill load volume can be also calculated with using Equation 9 if total ball tonnage value is known. All of the equations used to calculate the load volume are given below. Mathematical equation using X, Y measurements and geometry relations to calculate the load volume is given in Equation 6, proposed by Morrell in Equation 7, and proposed by Allis Chalmers Company in Equation 8. Basic notation used in calculations is given in Figure 3.

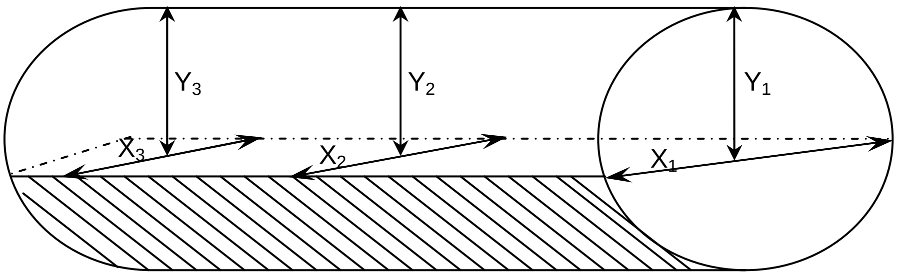


Figure 2. Mill inside measurement points

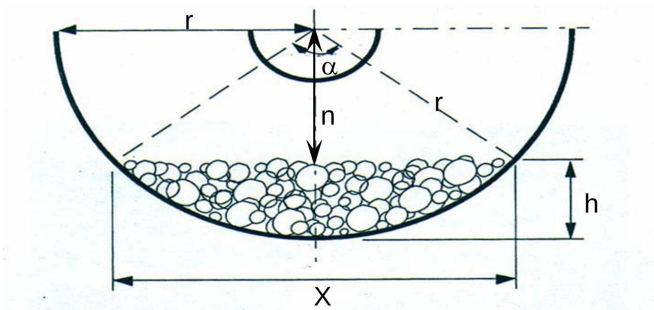


Figure 3. Cross section view of ball mill

$$\% \text{ mill load} = \frac{(A_\alpha - A_ü)}{A_d} \times 100 \tag{6}$$

$$\% \text{ mill load} = \frac{\left(\frac{h}{6X} \cdot \left(3h^2 + 4X^2\right)\right)}{A_d} \times 100 \tag{7}$$

$$\% \text{ mill load} = 113 - \left(\frac{Y}{D} \times 126\right) \tag{8}$$

$$\% \text{ mill load} = \frac{\left(\frac{10\, m_d}{6\rho_b}\right)}{A_d \cdot L} \times 100 \tag{9}$$

$A_ü$ – Area of triangle with n height and X base length, m^2
A_α – Area of arc with α angle, m^2
A_d – Area of circle with r radius, m^2
h – Height of mill load, m
X – Width of the charge, m
Y – Perpendicular distance between the charge and liner surface, m
m_d – Tonnage of ball in each compartment, ton
ρ_b – Density of ball, ton/m^3
L – Length of compartment, m
D – Radius of mill, m

POWER DRAW CALCULATIONS AND DISSCUSSION

In a cement plant mill load value calculated with different approaces are given in Table 2.

Table 2. Calculated mill load volume with using different calculation method for Çorum cement mill

Calculation Method	Mill Load Volume	
	1st Chamber	2nd Chamber
Geometric equation (Using measured horizontal (X) value)	32.04	24.55
Geometric equation (Using measured vertical (Y) value)	27.48	26.63
Allis Chalmers equation	27.19	26.30
Morrell equation	28.10	26.25
Mathematical equation (Using total ball tonnage value)	25.44	29.66

Representative samples were also taken from the material being ground in the mill to determine the bulk and specific gravity of the material after a crash stop of the mill. Specific gravity and bulk density of the materials were determined by using air-pycnometer and a graduated vessel respectively.

After these required measurements and mill load volume calculation which will be used in power model were obtained no-load power, charge motion power for first and second compartment and finally gross power were calculated separately. To illustrate the calculation steps a worked example is given for a cement ball mill. To execute the calculation certain design and operating data are required. These are summarized in Table 3.

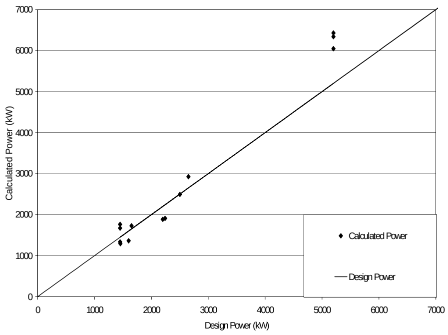
Table 3. Operating and design data for calculation

Operating and Design Variables [units]	Values
Mill diameter, [m]	3.27
1st chamber length, [m]	3.60
2nd chamber length, [m]	7.00
Total fractional mill filling of 1st chamber length, [%]	27.48
Total fractional mill filling of 2nd chamber length, [%]	26.63
Ball and void fractional mill filling of 1st chamber length, [%]	19.98
Ball and void fractional mill filling of 2nd chamber length,[%]	19.36
Mill rotational speed, [rev/min]	17.00
Fraction critical speed, [%]	72.67
Specific gravity of ore, [tons/m^3]	2.93
Bulk density of ore, [tons/m^3]	2.00
Specific gravity of balls, [tons/m^3]	7.80
Fractional porosity of charge	0.40

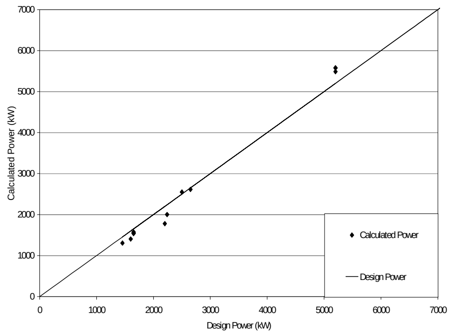
Calculation steps:

1. Calculate the charge motion power for first and second compartment. From Equation 3 first compartment charge motion power: 341.97 kW and second compartment charge motion power: 650.69kW.
2. Calculate the no-load power for first and second compartment. From Equation 5 first compartment no-load power: 41.94kW and second compartment no-load power: 72.35kW.
3. Calculate the gross power. Total power draw due to charge motion in the mill is 992.66kW, no-load power is 114.29kW and calibration factor that allows for heat losses and other energy consumed, k, is 1.26. From Equation 2: gross power (power input to the motor): 1365.04kW.

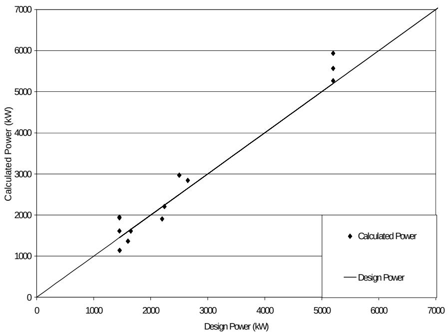
Graphically the accuracy of this new approach to calculate power draw of dry ball mills used in cement grinding is illustrated in comparisons of the observed and predicted power draws in Figure 4.



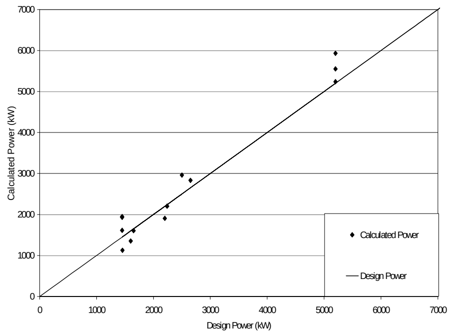
a – Calculated and design power values (Using measured horizontal (X) value mill load)



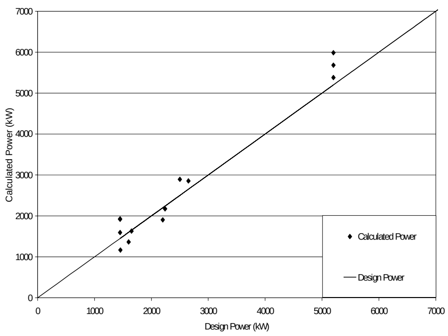
d – Calculated and design power values (Using Allis Chalmers equation mill load)



b – Calculated and design power values (Using measured horizontal (X) value mill load)



e – Calculated and design power values (Using total ball tonnage value mill load)



c – Calculated and design power values (Using Morrell equation mill load)

Figure 4. Observed vs design power consumption of ball mills

In order to design a ball mill and to calculate the specific energy of grinding, it is necessary to have equation(s) law which relates mill power and mill size and mill operating conditions.

Power draw varies as a function of ball loading and rotational speed. Lifter design is another parameter for the power draw of the mills. Although the cement mills sampled in this study have got similar ball loading, rotational speed and lifter desing, different mill power draws were recorded. The data give the opportunity to set the exact relationship between the mill diameter and power draw for the cement mills.

As mentioned in the context, there are some several ways of determining the load in the mill. Ball milling operations start with a design charge and under normal operating conditions. It is necessary to add the make up charge. This will cause loosing the mill load data at the sepecific circuit. Therefore, it is the best way to calculate the mill load is to get the measurements. In order to achieve the most efficient operation, mill conditions should be optimized and the choice of mill conditions are dependent on the economics of ball loading and wear.

In this exercise the success of the calculation methods are compared with the ball tonnage recorded during the plant survey. As given in Figure 4 the predictions give very good fit with the measured data.

CONCLUSIONS

A new approach based on Morrell's C model is used to calculate the power draw of dry multi-compartment ball mills. Calculated power draws were in good agreement with the measured values. Volumetric mill load calculated using different equations gave similar results. Increasing the number of measurements taken along the width and length of the mill would improve the accuracy of the calculation.

It was found that the power draw of dry multi-compartment ball mills used in cement grinding could successfully be predicted using this approach. However, this method needs to be validated with more data sets including variation of other operating parameters such as critical speed and lifter design.

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W pracy zaproponowano nowe podejście do problemu kalkulacji zużycia energii przez młyny kulowe pracujące „na sucho", stosowane do otrzymywania cementu. Dla realizacji tego zamierzenia, zgromadzone zostały dane operacyjne i projektowe z 14 instalacji przemysłowych, które zawierają młyny kulowe o średnicy w przedziale od 3,2 do 4,8 m. Załadunek kulami każdego młyna został zmierzony przy wykorzystaniu różnych metod, proponowanych w literaturze. Zużycie energii przez każdy z badanych młynów, zostało wyliczone. Otrzymane wyniki wskazują, ze zużycie energii przez młyny do produkcji cementu można dokładnie przewidzieć stosując metodę zaproponowana w pracy.