The Effects of Temperature, Vibration and Dosage on the Efficiency of Cement Grinding Ball Mill Motors*

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Normanyo, E. and Ofosu, R. A. (2021), "The Effects of Temperature, Vibration and Dosage on the Efficiency of Cement Grinding Ball Mill Motors", *Ghana Journal of Technology*, Vol. 6, No. 1, pp. 9-17.

Abstract

Ball mills as used in mining, cement production and allied industries consume about 40% to 56% of the total electric power supplied to the processing plant. Electric power losses in ball mill operations constitute about 25% of the available power. This paper reports on investigations into ball mill motor efficiency evidenced from a cement plant operations perspective. Basic theory was invoked to establish a relationship between electric power consumption and grindability factors. Temperature, vibration and dosage data were collected and analysed. Plots of mill motor efficiency against data-related influential ball mill factors were conducted. Results show that time of day, temperature, vibration and tonnage of ore strongly influence ball mill motor efficiency. Mill motor efficiency was found to decrease in the afternoons. A lowest efficiency of 93% corresponded to trunnion bearing temperature, pinion bearing temperature, mill motor temperature, mill motor vibration, pinion gear vibration of 46.04 ºC, 44 ºC, 59 ºC, 1.48 mm/s^2 and 1.57 mm/s^2, respectively. Decrease in any of the influential factors considered improved ball mill efficiency accordingly.

Keywords: Ball Mill, Cement Grinding, Mill Dosage, Mill Motor Efficiency, Temperature, Vibration

1 Introduction

Cement is paramount for economic development and poverty reduction in developing countries such as Ghana that are witnessing rapid urbanisation. Cement is manufactured from clinker, gypsum and limestone. In 2016, 4.1 billion tons of cement were consumed worldwide in emerging markets contributing at least 5% of anthropogenic Greenhouse Gas Emissions (GHG). The energy-related expenses in the cement sector, mostly on fossil fuels and electricity, account for 30 to 40% of the industry's cash costs (Cantini *et al*., 2021; International Finance Corporation, 2017; Worrell *et al*., 2013). Cement is produced from raw materials such as limestone, chalk, shale, clay, iron ore and sand and it is resource-intensive with regard to raw materials, energy, labour and capital (Atmaca *et al*., 2012; Fellaou and Bounahmidi, 2017). Raw material preparation is electricity-intensive demanding about 25 to 35 kilowatt hours (kWh) per ton of raw material (International Finance Corporation, 2017).

Further reduction in size of the raw materials is achieved by finish grinding in ball mills after primary and secondary size reductions (Atmaca *et al*., 2012; Cantini *et al*., 2021). Finish grinding involves the largest unit consumption of electric power in cement manufacture. Approximately 2% of the global primary energy, or 5% of global industrial energy, is consumed in cement production, of which 85 - 90% is thermal energy and 10 - 15% is electricity. About 25% of the cement cost is due to energy costs, of which approximately 50% is for electricity, mainly for grinding (Altun *et al*., 2020; Atmaca and Atmaca, 2016; Ghalandari *et al*., 2019).

In a typical cement plant, 65% of the electricity consumed is used in the grinding operations (Altun *et al*., 2020; Atmaca and Atmaca, 2016; Ghalandari *et al*., 2019). According to Worrell *et al*. (2013), power consumption for grinding depends on the surface area required for the final product, hardness of the material and the additives used. Traditionally, ball mills are used in finish grinding. In the ball mills, the clinker and gypsum are fed into one end of a horizontal cylinder and cement exits from the other end. Modern ball mills may use between 32 and 37 kWh/ton of electrical energy (Worrell *et al*., 2013). The power consumption of a ball mill rated 2.5 MW stands at 27.5 kWh/t of cement produced making the grinding inefficient and much of the lost energy goes to heat, friction wear, noise and sound, and vibration (Atmaca *et al*., 2012). Improvements therefore, in the energy efficiency of finish grinding of cement are of great economic significance as they hold much promise for mill output and enhancement of productivity (Altun *et al*., 2020; Cantini *et al*., 2021; Mokhtar and Nasooti, 2020).

Cost efficiency occurs when machinery increases output power without increasing the amount of input power used thus, maximising the work done by minimising losses due to heat and friction. The key to reaching this high efficiency is further improvement in appropriate operation of machinery and effective maintenance. The comminution processes in the cement industry are synonymous with ultimate size reduction in tumbling mills and are known to be both energy–intensive and expensive. In the context of high electricity prices and demand for high throughput, efficiency of ball mill motors in cement finish grinding can be

*Manuscript received June 09, 2021
Revised version accepted September 17, 2021*

improved to ensure stable and power-efficient operation at high production rates. Grinding system performance in the cement industry is influenced by material characteristics, moisture in feed materials, energy costs, maintenance and investment. Responsible and efficient operation of grinding circuits is critical; hence, process optimisation study is initiated to improve plant performance in terms of optimum capacity utilisation, reduction in maintenance costs, improved product quality and improved consistency in plant operation (Swanepoel *et al*., 2014). The most important properties of cement, such as strength and workability, are affected by its specific surface and by the fineness and width of the particle-size distribution. These can be modified to some extent by the equipment used in the grinding circuit, including its configuration and control (Genç, 2016). Grinding, because it is normally the final stage of comminution, takes on special importance and is often described as the key to successful plant operation and production (Altun *et al*., 2020; Mokhtar and Nasooti, 2020). Grinding takes place due to the energy interaction between the balls and materials. Potential, kinetic and heat energies are involved with regard to movement of grinding media in the rotating ball mill.

A considerable amount of research was conducted and reported on regarding energy efficiency improvement options in the finish grinding of cement (Altun, 2016; Altun *et al*., 2020; Camalan and Hoşten, 2015; Cantini *et al.*, 2021; Chowdhury *et al.*, 2018; Fawkes *et al.*, 2016; Fellaou and Bounahmidi, 2017; Genç, 2016; International Finance Corporation, 2017; Mokhtar and Nasooti, 2020; Pech *et al.*, 2021; Swanepoel *et al*., 2014; Szegvari and Yang, 2021; Telichenko *et al.*, 2016; Worrell *et al.*, 2013; Zhang *et al.*, 2021).

Very few research were devoted to the influence of operational variables such as insulated cyclones and gas channels (Atmaca *et al*., 2012), refractory bricks and anzast layer formation (Atmaca and Yumrutas, 2014), temperature (Atmaca and Kanoglu, 2012; Atmaca *et al*., 2012; Atmaca and Yumrutas, 2015), moisture content (Atmaca and Kanoglu, 2012), vibration (Atmaca and Atmaca, 2016) and mill dosage (Gómez Sarduy *et al*., 2013) on the efficiency of the mill drive motor in the cement industry. These researches were devoted to the raw mill for farine production which is the semi-product of clinker or a pyro processing unit or a rotary kiln all of which are used in the production of cement. However, effects of temperature, vibration and mill dosage on the ball mill drive motor efficiency in cement finish grinding has not been investigated to the best of our knowledge hence, the focus of this paper. The rest of the paper is structured as follows: Basic theory on comminution energy, grindability and critical speed, together with data collection are covered in Section 2. Section 3 gives the results and discussion, and the conclusion is presented in Section 4.

2 Resources and Methods Used

In this investigation, basic theory was invoked to establish the underlying relationships between electrical energy utilized and ball mill grindability factors. Data on temperature, vibration and mill dosage were gathered from a cement manufacturing company in Ghana. The efficiency of ball mill motor was also calculated from voltage and current data readings at a power factor of 0.9.

2.1 Ball Mill in Cement Finish Grinding

Materials such as clinker and additives fed through the mill are crushed by impact and ground by attrition between the balls. The grinding media are usually made of cast iron. At a critical speed the contents of the mill ride over the roof of the mill due to centrifugal action. Conventional ball mills in cement manufacturing are characterised by shorter length to diameter ratios of 3:1 or less. A typical layout of a ball mill utilised in finish grinding in the cement manufacturing industry is shown in Fig. 1. The grinding action in a ball mill is a purely random process. Ball mills are normally operated at around 65 - 75% of critical speed (Alsop, 2019; Gupta and Yan, 2016). Optimisation of electrical energy in cement ball mills helps in increasing mill efficiency and effectiveness.

2.2 Theoretical Background

Inefficiency occurs in a ball mill when overworked by running at increased speeds, friction or at high operating temperatures causing overheating or breakdown (Chowdhury *et al*., 2018). As volumetric dosage entering the mill increases, the motor draws more current (Gómez Sarduy *et al*., 2013). The power drawn is directly proportional to the current consumed so as current increases the mill consumes more energy (Atmaca and Atmaca, 2016; Gómez Sarduy *et al*., 2013). In operating the ball mill with ball filling degree higher than the optimum, a waste of energy occurs because the ball wear rate is proportional to the surface of the media charge and an extreme wear of balls occurs as well (Genç, 2016). The grindability of the ore therefore, increases up to the optimum after which wear begins. The mill draws more power as the charge entering increases (Atmaca and Atmaca, 2016).

The mill speed must not be more than the critical speed because anything above the critical speed will cause the balls to attach themselves to the mill shell and will not be able to tumble for the grinding process to be possible (Alsop, 2019; Gupta and Yan, 2016).

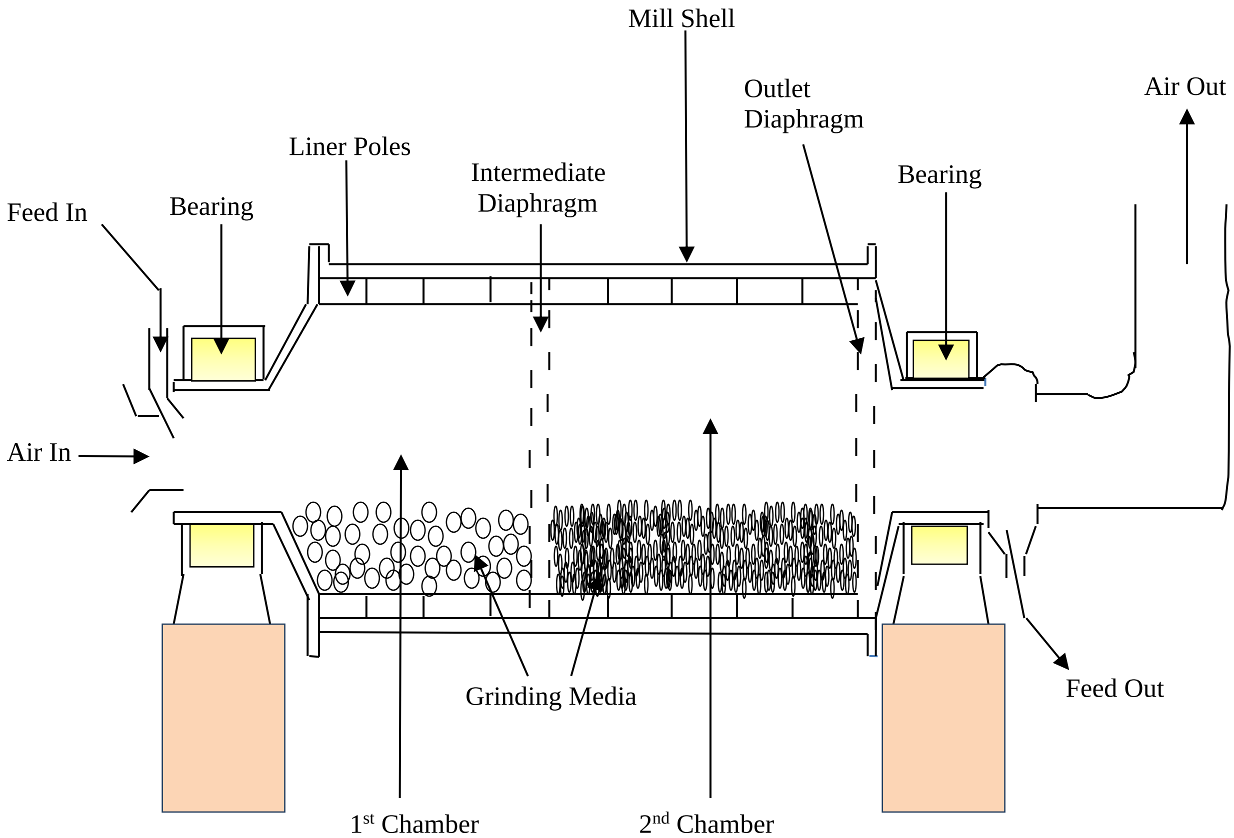

Fig. 2 A Schematic Diagram of a Two-Compartment Ball Mill Used in Cement Finish Grinding

The power draw increases with the grindability up to the critical speed level of the mill. The mill draws more power as the dosage increases to increase grindability of the mill. But as the mill draws more power, its temperature and that of the bearings and the gears also increase (Atmaca and Kanoglu, 2012; Atmaca and Yumrutas, 2015). The temperature of the bearings and therefore, the mill itself must be controlled.

2.2.1 Mill Dosage

For the two compartment cement ball mill operated in closed circuit, the product size distribution is expressed by Equation (1) (Gupta and Yan, 2016).

$$P = \frac{(I - C)(BS + I - S)}{I - C(BS + I - S)} \times F_1 \qquad (1)$$

where, P is product vector for size distribution (mass), B is breakage function, S is selection function, C is classification function, F_1 is new feed in tonnes per hour, and I is unit diagonal matrix.

The charge volume loading of mill is expressed using Equation (2).

$$V_c(\%) = \left(\frac{\theta}{3600} - h\sqrt{r^2 - h^2}\right) \times 100 \qquad (2)$$

where, V_c (%) is charge volume loading of mill in percentage, r is effective mill radius in meters, h is (H – r) in meters, H is free height in meters, and θ is angle subtended at mill axis by charge surface whereby $\cos\left(1/2\,\theta\right) = h/r$. The ball mill media charge wear rate is given by Equation (3).

$$W_t = \frac{d(m_b)}{d(t)} = -k_m A_b \qquad (3)$$

where, W_t is mass wear rate in kg/hr, m_b is ball weight in kg, after t hours of being charged into the mill, A_b is exposed ball area in m^2 and k_m is mass wear rate constant in kg/hr/m^2.

2.2.2 Energy Consumption

The energy in kWh required to produce a tonne of finished cement referred to as the specific energy consumption, is given by Equation (4).

$$E_{cs} = \frac{P_D}{F_1} \qquad (4)$$

where, E_{cs} is the specific energy consumption in kWh, P_D is the mill power draw in kW. The mill power draw is given by Equation (5).

$$P_D = 10\,W_i\left(\frac{1}{\sqrt{F_1}} - \frac{1}{\sqrt{P_1}}\right)C_1\,C_2 \qquad (5)$$

where, P_D is the mill power draw in kWh/tonne, W_i is Bond work index in kWh/tonne, F_1 is the micron size at which 80% of feed passes, P_1 is the micron size at which 80% of product passes, C_1 is a coefficient equal to 1.3 for dry grinding, C_2 is a coefficient equal to $(2.438/D)^{0.2}$ where D is effective mill internal diameter in meters. The Bond work index (W_i) expresses resistance of the material to grinding and it is the gross energy required in kilowatt-hours per tonne of feed needed to reduce a very large feed to such a size that 80% of the undersize passes through 100-µm screen (Gupta and Yan, 2016). The Bond work index is expressed by Equation (6).

$$W_i = \frac{435}{(HGI)^{0.91}} \qquad (6)$$

where, HGI is Hardgrove grindability index.

2.2.3 Hardgrove Grindability Index

The Hardgrove Grindibility Index (HGI) of cement is an evaluation indicator of its grindability characteristics to determine the energy required for its grinding. It is a predictive measure to assess the performance of industrial milling machines such as the ball mill in terms of energy required for grinding. It is a determining factor of energy consumption during grinding. Useful to this research is the relation of HGI to ball mill operational parameters notably temperature, vibration and mill dosage as expressed in the functional expression in Equation (7).

$$H_g = f\left(k_h \times V_c \times T_m \times P_D \times V_b\right) \qquad (7)$$

where, k_h is a constant, T_m is mill temperature and V_b is mill vibration.

2.2.4 Critical Speed

The mill critical speed is calculated using Equation (8) (Gupta and Yan, 2016).

$$N_c = \frac{42.29}{\sqrt{D}} \qquad (8)$$

where, N_c is critical speed in revolutions per minute and D is inner mill diameter in meters If the peripheral speed of the mill is very high, it begins to act like a centrifuge and the balls do not fall back but rather stay on the perimeter of the mill at the 'critical speed', N_c.

2.2.5 Mill Motor Efficiency

The mill motor efficiency is given by equation (9).

$$\eta_m = \frac{E_o}{E_i} \times 100\% \qquad (9)$$

where, η_m is mill motor efficiency, E_o is the output electrical energy of mill motor and E_i is the input electrical energy of the mill motor. The output and input electrical energies of mill motor are given by Equations (10) and (11), respectively.

$$E_o = P_s \times t \qquad (10)$$

$$E_i = S_i \times t \qquad (11)$$

where, P_S is the motor output power available at the shaft, S_i is the motor input power and t is time in hours used in running the mill. The input and output power of the electric motor are expressed using Equations (12) and (13), respectively.

$$P_S = \frac{\sqrt{3} \times i_m \times V_L \times \cos\phi \times \eta_m}{1000} = T_{em} \times \omega_m \qquad (12)$$

$$S_i = \frac{\sqrt{3} \times i_m \times V_L}{1000} \qquad (13)$$

where, i_m is the current drawn by motor, V_L is input line voltage, $\cos\phi$ is the power factor, ϕ is the phase angle between the current and voltage, T_{em} is the electromagnetic torque developed by mill motor and ω_m is the rotational speed of mill motor.

2.3 Data Collection

Mill power loss is the electrical energy wasted due to heat or frictional loss in the ball mill itself or in the auxiliaries, especially, in the bearings per unit time. Vibration also contributes towards losses. Field data regarding mill temperature were taken at both drive and non-drive ends of the trunnion bearings, the pinion bearings and the ball mill motor. The temperatures were taken every thirty (30) mins of the day from 7:30 am to 7:30 pm using the SKL Dual Laser Infrared Thermometer (DLIT). Vibration data for every thirty (30) mins were obtained by the vibration monitoring sensor BMM 42 attached to the pinion gear through the bearing monitoring module to the Supervisory Control and Data Acquisition (SCADA). The minimum, maximum and average temperatures for the day and vibration values are as given in Table 1 and Table 2, respectively. The mill dosage was taken using a mass flowmeter with the corresponding input power to the motor for every thirty (30) minutes monitored from the SCADA and recorded. The current drawn by the mill was also monitored from the installed ammeter.

3 Results and Discussion

The main parameter of interest is the ball mill electrical power efficiency. The parametric influe-nces on ball mill electrical energy efficiency and measures required to optimise this efficiency were of paramount importance. Respective graphs were generated from the analysed data.

3.1 Results

Mill motor drive efficiency is used to analyse the electrical energy efficiency of the ball mill. The results of variation of mill motor efficiency with time of day, temperature, vibration and tonnage of ore are presented in Figs. 2 to 8 based on the analysed data.

3.2 Discussion

Generally, mill motor efficiency decreases after about five hours of operation when the daily temperature and heat generated by mill are higher and conversely, the efficiency gets higher in the mornings and the evenings (Fig. 2). Mill motor efficiency sharply drops from 12 noon from 96% to 94% and hits 93% at 14:30 pm. The efficiency starts to rise at 16:30 pm reaching a maximum value of 97.5% at around 19:00 pm. Clearly, time of day affects ball mill efficiency. From Figs. 3, 4 and 5, it could be stated that generally, high temperatures result in lower efficiencies. Efficiency increases up to a trunnion bearing temperature of 45.16 ºC. As the temperature increases, the efficiency decreases. At the onset of slight decrease in temperature, the efficiency is seen improving again

Table 1 Summary of Temperature Variations

Equipment	Minimum Temperature (ºC)	Average Temperature (ºC)	Maximum Temperature (ºC)
Trunnion Bearing	45.09	45.62	46.00
Pinion Bearing	39.00	42.77	45.00
Mill Motor	55.00	57.42	59.00

Table 2 Summary of Vibration Variations

Equipment	Minimum Vibration (mm/s^2)	Average Vibration (mm/s^2)	Maximum Vibration (mm/s^2)
Mill Motor	1.39	1.43	1.51
Mill Pinion Gear	1.07	1.21	1.45

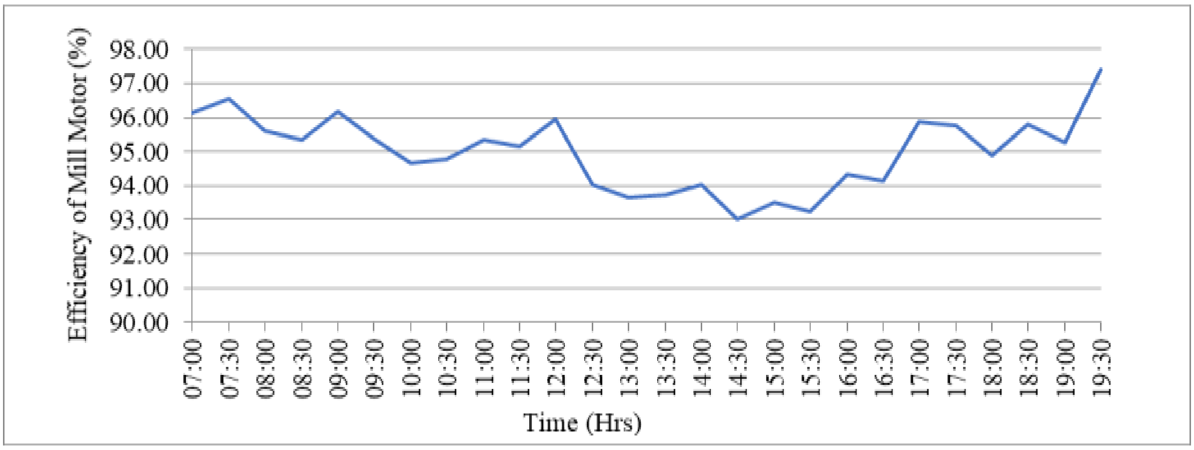

Fig. 2 A Graph of Mill Motor Efficiency versus Time

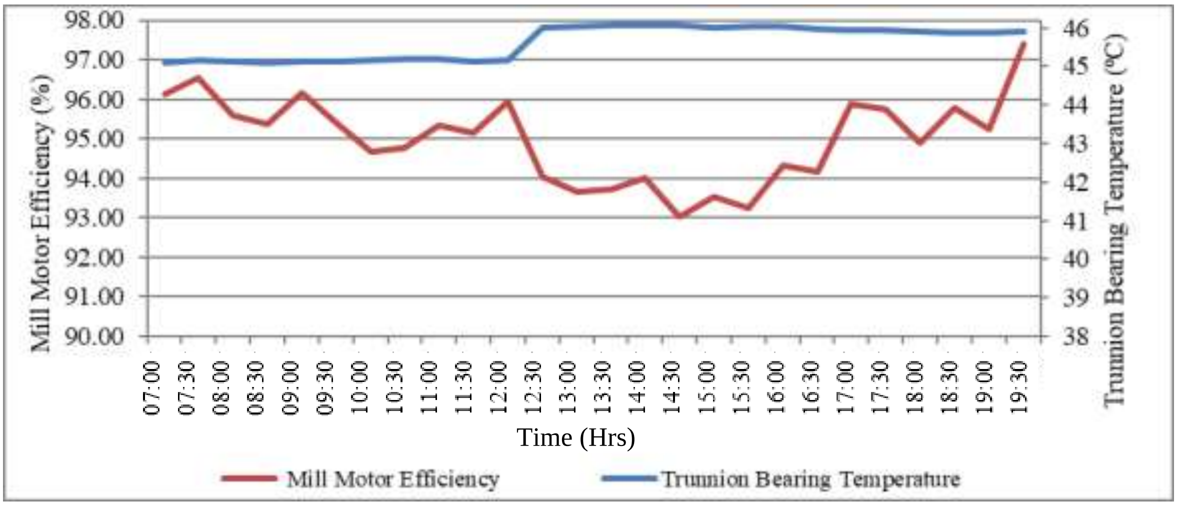

Fig. 3 A Graph of Mill Motor Efficiency and Trunnion Bearing Temperature versus Time

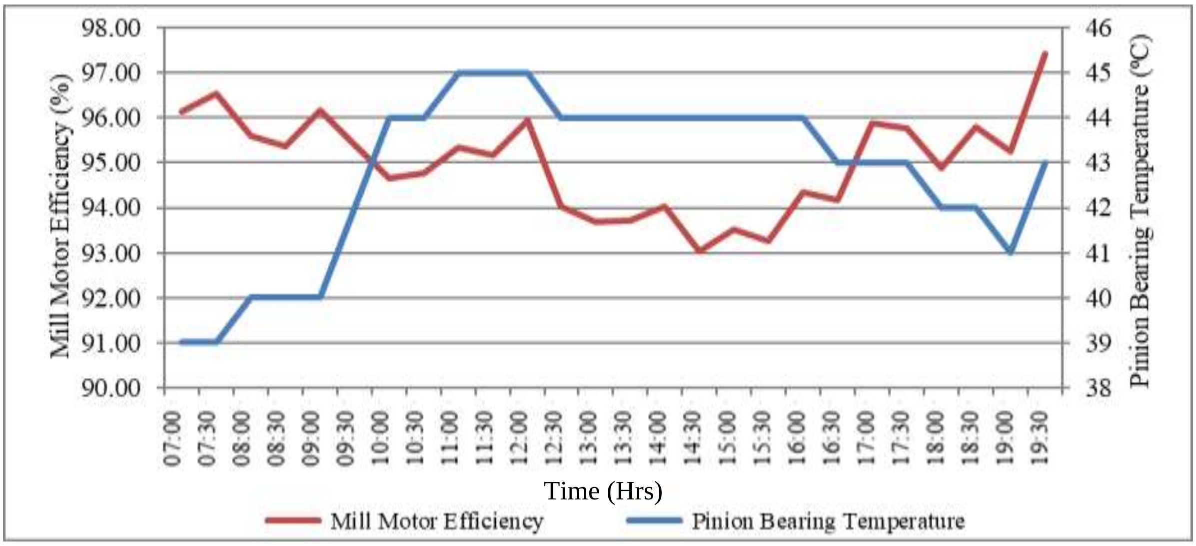

Fig. 4 A Graph of Mill Motor Efficiency and Pinion Bearing Temperature versus Time

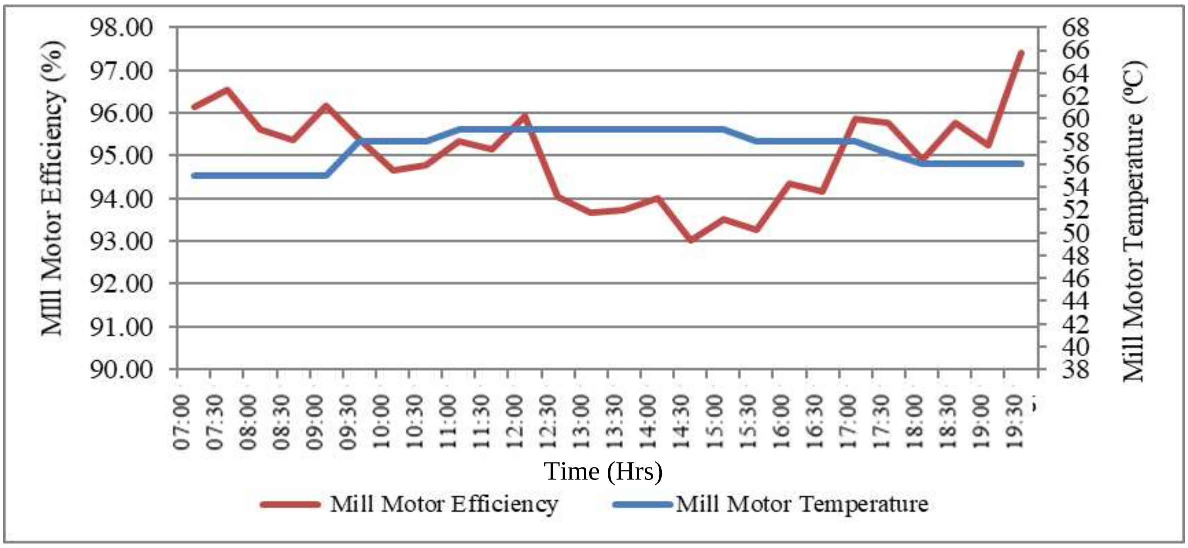

Fig. 5 A Graph of Mill Motor Efficiency and Mill Motor Temperature versus Time

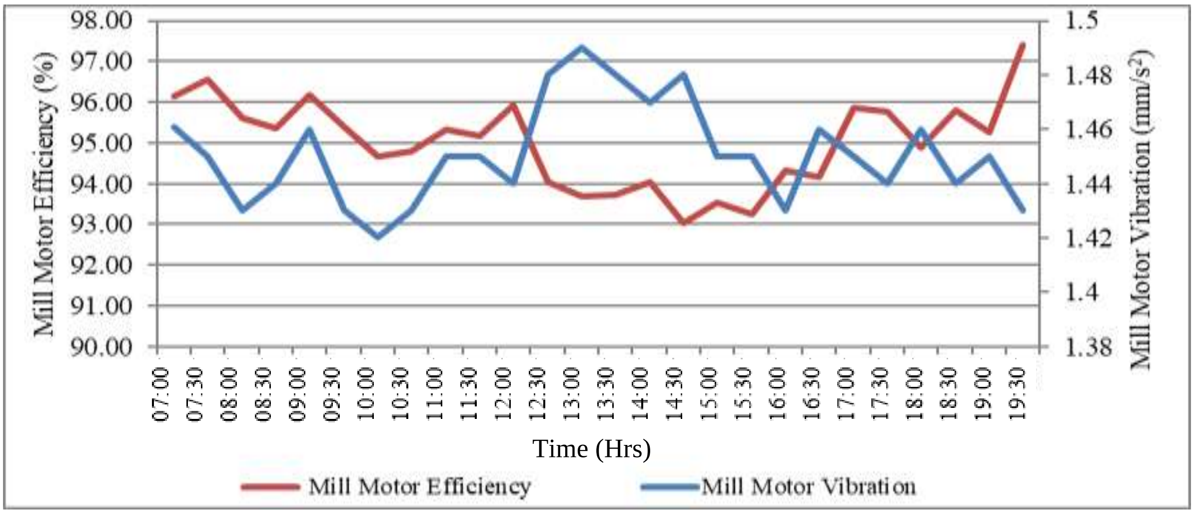

Fig. 6 A Graph of Mill Motor Efficiency and Mill Motor Vibration versus Time

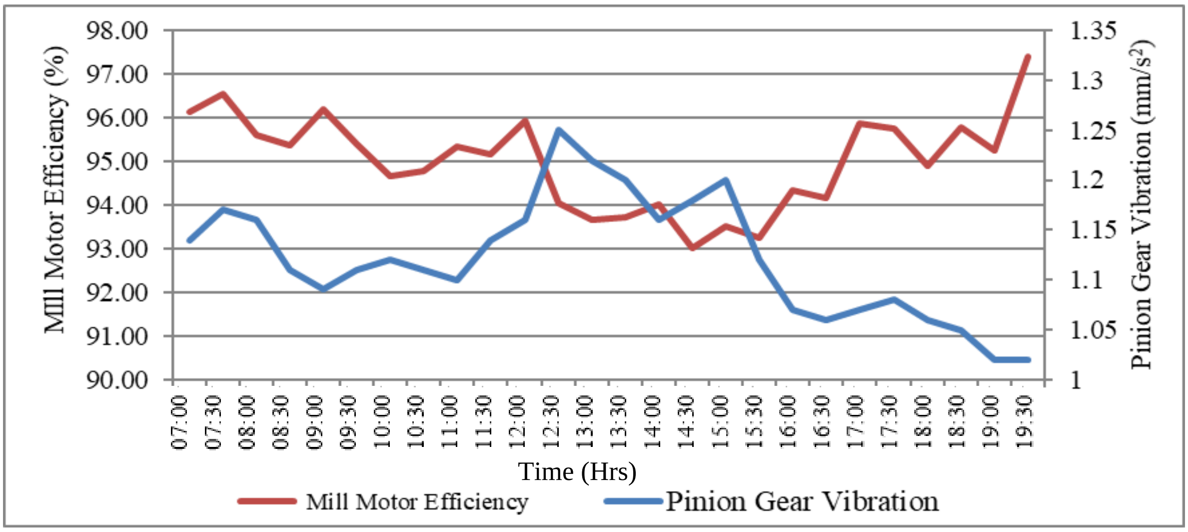

Fig. 7 A Graph of Mill Motor Efficiency and Pinion Gear Vibration versus Time

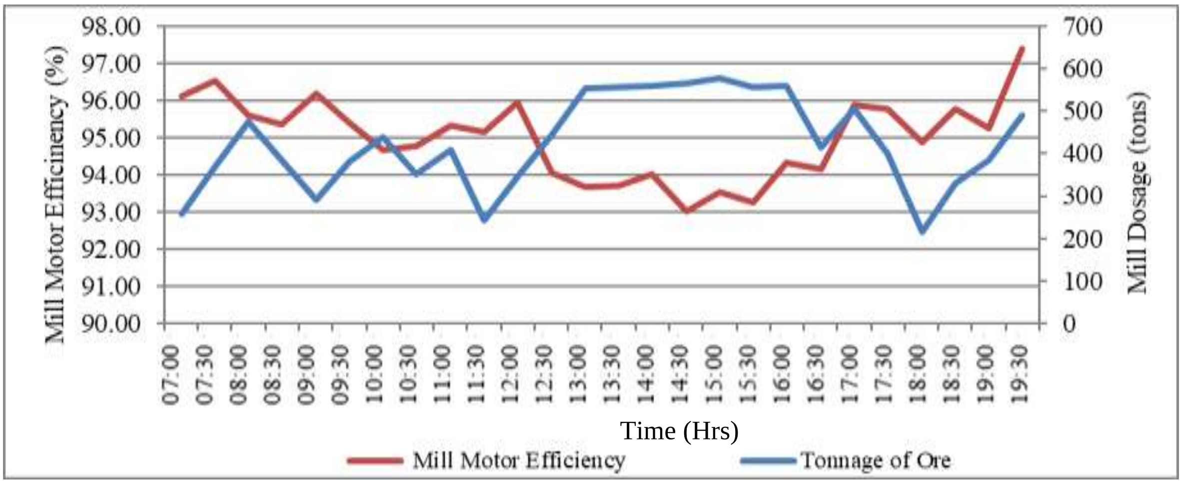

Fig. 8 A Graph of Mill Motor Efficiency and Mill Dosage versus Time

A lowest efficiency of 93% occurred at a maximum trunnion bearing temperature of 46.04 ºC (Fig. 3) whilst the same lowest efficiency is observed for a pinion bearing temperature of 44 ºC (Fig. 4) and motor temperature of 59 ºC (Fig. 5). The lowest efficiencies appear to be occurring in the afternoons where temperatures are far higher. Secondly, higher temperatures above 54.2 ºC signifying more losses, occurred in the mill motor as it is the main motor driving the mill and exhibits the greatest heat loss.

From Figs. 6 and 7, it can be said generally that low vibration levels result in higher mill motor efficiencies and vice versa. A lowest mill motor vibration level of 1.42 mm/s^2 occurred at an efficiency of 94.66% and the highest vibration level of 1.49 mm/s^2 gave an efficiency of 93.72%. A lowest pinion gear vibration level of 1.025 mm/s^2 recorded mill motor efficiency of 97.47% and the highest vibration level of 1.25 mm/s^2 gave 94% efficiency. The lowest efficiency of 93% occurred for the mill motor vibration level of 1.48 mm/s^2 and pinion gear vibration level of 1.57 mm/s^2.

Fig. 8 underlines the fact that the more the mill dosage, the more reduced the mill motor efficiency. A lowest dosage of 216 tons gave an efficiency of about 94.89% whilst 578 tons being the highest dosage resulted in 93.52% efficiency. A lowest efficiency of 93% occurred very close to the highest mill dosage. It is however known that when the material is too small, energy is wasted as the grinding media hit each other without affecting enough grind. Also, when the material is too much for the mill, the grinding media are not able to grind efficiently. The efficiency therefore decreases as the material dosage fed into the mill increases as seen in Fig. 8.

From the basic theory and results obtained, it is clear that electrical energy efficiency of the ball mill motor drive is affected by temperature of the trunnion bearings, temperature of pinion bearings, temperature of the mill motor, vibration of pinion gear, vibration of mill motor, tonnage of material fed into the mill (overloading and underloading) and overspeeding of the mill causing centrifuging.

4 Conclusion

A ball mill motor electrical energy efficiency optimisation in cement clinker grinding has been investigated. The focus has been the influences rendered by temperature, vibration and dosage on mill efficiency. We conclude this investigation by stating that efficiency of mill motor decreases as temperature of trunnion bearing, pinion bearing and mill motor increases and vice versa. As vibration of the mill motor and the pinion gear increases, efficiency of the mill motor decreases and vice versa. Tonnage of material fed into the mill is inversely proportional to the mill motor efficiency. Critical speed is relevant to the efficient operation of the ball mill. To optimise the drive motor energy efficiency, there is need to improve upon minimising temperature of the bearings, the mill motor and other accessories by way of increased ventilation and cooling; minimisation of vibration by way of optimising mill maintenance. Also, mill input should be constantly controlled to keep the electrical energy efficiency as high as possible.

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