A statistical analysis and optimization of Indian coal grinding in a laboratory ball mill: dry & wet method

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This study explores the different product particle size of coal while applying dry and wet grinding and optimization of parameters affecting the grinding process with both methods. Grinding of coal up to μm size is indispensable to achieve its maximum calorific value and better combustion. A systematic experiment, as well as modeling of grinding of Indian coal of size -3.5 +1 mm was done by response surface methodology. There were five different parameters chosen, which were found to be affecting the grinding process, namely: amount of feed (100-150-200 g), ball mill rotational speed (20-30-40 rpm), time of grinding (4-7-10 min), and number of balls (10-15-20); in case of wet grinding amount of water (10%-20%-30% of feed by weight) was added. Effect of parameters and their interaction on the fineness was evaluated by Box-Behnken design and ANOVA. Moreover, wet grinding shows better results of fineness of coal. Grindability of the coal was tested by standard Bond grindability test and calculated from breakage rate by Mohs' hardness. Experimental results are in good agreement with model equation and regression coefficient (R^2) was obtained to be 0.97 and 0.98 for dry and wet grinding, respectively.

Keywords: Grinding of coal, Surface response methodology, Dry and wet grinding, Ball mill, Box-Behnken design.

INTRODUCTION

India is the third-largest country after USA and China in energy consumption. The demand is increased by 7.9 % in 2018, and its global share is 5.8 %. The total primary energy consumption from coal is 452.2 metric tons which is 55.88 % of total energy required in the calendar year 2018. As per consumption and population, India is largely dependent on coal imports to fulfill its energy demands by 2030; India's dependence on energy imports is expected to exceed 53% of the country's total energy consumption. Nonetheless, the requirement of energy to grind coal up to 100 μm is huge, but the efficiency of combustion increases with decreased particle size [1].

Preheating coal in an oven has been shown to reduce grind strength, although it is unlikely that this would be an economically possible method, at least not through associated energy requirements [2]. Fine particles of coal have several applications like coal water slurry [3, 4], micro size coal in cement clinker production, coal beneficiation of air-fluidized bed, reduction of sulfur, ash and other impurities in micro size coal particles [5, 6]. Mineralogical characteristics of materials and operating variables noticeably affect the fineness of coarse particles [7, 8]. These parameters include the mill speed, ball size, filling rate, feed size distribution, pulp density and material hardness. According to [9], pulp density has the most significant effect on the fineness of particles. Most fine particles were obtained at 45 vol. % solid concentration of copper ore, quartz and coal.

In a previous study [10], dry grinding of coal in a laboratory ball mill showed that grinding is most influenced by the amount of feed and time of grinding. In another reference, ball charge has been found to have a significant effect on the product fineness for same specific energy consumption and increases power draws of the mill linearly [11]. In a study, the charge ratio, Bond work index and the ball diameter of Turkish coal and ore grinding were taken as the variables in the experiments, however, time of grinding is also an important parameter to decide the fineness in the grinding experiments [12, 13]. The ash content was quite low compared to the Indian coal. The ball size should be large enough and weight of balls must be sufficient to grind the charge efficiently. The current work uses constant ball size, and these are considered to be efficient for the grinding media.

Fine grinding being of importance for liberation of coal and attaining maximum calorific value, further enhancement in the performance of ball mill can be obtained by evaluating the effects of operating parameters on mill efficiency. The number of balls, feed size, time of grinding, rotational speed and grinding aid as water for wet grinding were considered to be controlling factors. The grinding and breakage of particles may depend on different parameters as discussed earlier. The effect of optimum parameters on fine grinding with dry and

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wet methods was found using Box-Behnken design and ANOVA. MATLAB code and Microsoft Excel were used to regress from the model.

Standard Bond grindability test for coal

The Bond grindability test is a closed loop grinding and screening process, which is continued until steady state conditions is achieved. Applying the Bond test it is assumed that all particles break similarly then only equilibrium or steady state is achieved. The test was executed by packing the coal and grinding media with 2000 cm^3 volume. This volumetric weight was used for the grinding tests. From the beginning of the cycle the ball mill was operated at 25 rpm for 30 min, arbitrarily chosen below the critical speed. At the end of each grinding cycle, the product was poured from the mill and screened on the test sieve (P_i). The oversize material was sent back to the mill along with fresh feed to maintain 2000 cm^3 volume. The weight of product per unit of mill revolution is named as ore grindability of the cycle, it was used to calculate and estimate the number of revolutions required in second cycle, it was equivalent to 250 % of the circulating grinding media and feed. This process was continued until equilibrium was attained for the grindability which arises in 6-12 cycles. After achieving equilibrium, the last three values were considered as the average standard Bond grindability. The products of the final three cycles were combined to form the equilibrium rest product. Sieve analysis was done for 80% passing size of the product.

After crushing the samples in a jaw crusher and roll mill, standard grindability tests were performed. The Bond work index (W_i) was calculated as Equation 1:

$$W_i = 1.1 \times \frac{44.5}{P_i^{0.23} G_b^{0.82}\left[\left(\frac{10}{\sqrt{P_{80}}}\right)-\left(\frac{10}{\sqrt{F_{80}}}\right)\right]} \quad (1)$$

where W_i is the work index in kWh/t; P_i, test sieve size at which test had been performed; G_b, Bond's ball mill grindability, net weight of ball mill product passing 80 % of test sieve per cycle (g/cycle); P_{80}, sieve opening of 80 passing; F_{80}, sieve opening 80 % of feed passing. For each coal sample all the parameters mentioned were calculated and W_i is reported in Table 1.

MATERIALS & METHODS

Coking coal which was collected from the overflow stream (washed coal) of a dense medium cyclone at Gujarat Mineral Development Corporation, Gujarat, was used as the raw material. A jaw crusher and a roll mill were used to prepare particles for grinding in a ball mill. The particle size initially present was of 4-5 mm. The d_{80} size of coal particles for ball mill feed was -3.5 +1 mm. Grinding tests were performed in a cylindrical laboratory-scale ball mill and specifications of the ball mill and balls are mentioned in Table 2. The rotation speed of the ball mill was kept below the critical speed.

Table 1. The values of F_{80}, P_{80}, G_b and W_i of different dry and wet coal samples.

Coal	F_{80} (μm)	P_{80} (μm)	G_b (g/cycle)	W_i (kWh/t)
Dry coal	385	2.15	7562	16.23
Coal with 10% water of feed	372	2.02	7845	14.25
Coal with 20% water of feed	387	1.84	7926	14.21
Coal with 30% water of feed	385	1.75	7985	14.23

Table 2. Specification of sample and ball mill

Mill	Inner diameter (D), cm	21
	Length, cm	25
	Operational speed (N, rpm)	20, 30, 40
	Critical speed (N_c, rpm)	121-133
Media charge	Materials	Alloy steel
	Mass of a ball, gm	67
	Ball diameter, (d) cm	2.4
	Ball density, g/cm^3	7.6
Material	Sample	coal
	Moisture, %	5.35
	Volatile compounds, %	18.65
	Fixed carbon, %	35.6
	Ash content, %	40.04
	Calorific value	4766 Cal/g
Critical speed[a] calculation	$N_c = \frac{30}{\pi}\sqrt{\frac{2g}{(D-d)\sin\beta\sqrt{1}}}$	

[a] In critical speed, it is to be noted that φ is the filling ratio of grinding media and charge volume to the mill volume which is 0.19-0.23, it is kept below 0.6 in a ball mill. β is the material angle of repose for balls, 29˚.

Response surface methodology

Conventional method takes much longer time to find the optimum parameters and does not provide any information regarding interaction of parameters to each other and parameters combined effect is not perceivable on the response. The minimum number of experiments to be performed according to the Box-Behnken design can be found by the following equation:

$$N = 2N_f\left(N_f - 1\right) + C_p \quad (2)$$

where N_f is the number of parameters used to fit the model, and Cp is the number of the central points. A design matrix accordingly was prepared for dry and wet grinding in Tables 3 and 4, respectively.

A Box-Behnken design with three levels was employed to evaluate the effect of different independent parameters on coal grinding. To find the optimum conditions, a quadratic model was used to relate the grinding of coal to independent parameters:

$$y = \alpha_0 + \sum_{j=1}^{n} \alpha_j x_j + \sum_{j=1}^{n} \alpha_{jj} x_j^2 + \sum_{j=1}^{n-1} \sum_{k=2}^{n} \alpha_{jk} x_j x_k + \delta \quad (3)$$

The set of a regression coefficient α's is unknown and estimated by the least square method. In a vector matrix, the equation for the least square fit can be represented by:

$$Y = X\alpha + \delta \quad (4)$$

where Y is defined as the measured value and X to be a matrix of independent variables.

Regression coefficient α can be found by the non-singular regression matrix transpose X'.

$$\beta = (X'X)^{-1}X'Y \quad (5)$$

where X' is the transpose of the matrix X and $(X'X)^{-1}$ is the inverse of the matrix $X'X$.

So these first four independent parameters for dry grinding and five independent parameters for wet grinding were coded at three levels with the same step size; that are +1, 0, and -1, where +1 represents the maximum value, 0 represents the centre, and -1 represents the minimum value of each parameter which was considered for analysis. Within the present research framework, the discussion was focused on the effect of the number of balls (*A*), amount of feed charged (*B*), grinding time (*C*), rotational speed (*D*) for dry grinding. An additional parameter the amount of water (*E*) was also included in wet grinding on the fineness of coal using a Box-Behnken design.

RESULTS AND DISCUSSION

Statistical analysis with Box-Behnken design

The independent parameters and their levels are presented in Table 2. If the total number of variables along with full factorial is considered $(3)^4$, 81 experiments will be required. Instead of doing that many experiments, the Box-Behnken design required 27 experiments as per the design. Eq. (2) represents the model equation which correlates the response which is a fineness (d_{80}) and different independent parameters for dry grinding. In wet grinding an independent parameter amount of water is also considered. Due to increase in the number of parameters, the number of experiments as per Box-Behnken design is also changed to 47 experiments. The model equations for both conditions are given below.

dry grinding:

$$d_{80} = 5.319 - 0.077A - 0.017B - 0.021C - 0.0218D + 0.00023AB - 0.0026AC - 0.0009AD + 0.00015BC - 0.00004BD - 0.0027CD + 0.0024A^2 + 0.00005B^2 + +0.006C^2 + 0.0008D^2 \quad (6)$$

wet grinding:

$$Y_{d80} = 9.922 - 0.303A - 0.013B - 0.4206C - 0.4206C - 0.0681D - 0.077E - 0.00027AB + 0.016AC + 0.001AD + 0.0016AE + 0.00019BC - 0.00047BD - 0.00015BE - 0.002CD + 0.0017CE + 0.003DE + 0.004A^2 + 0.00012B^2 + 0.005C^2 + 0.00009D^2 - 0.00022E^2 \quad (7)$$

where *A* is the number of balls; *B* is the amount of feed; *C* is the time of grinding; *D* is the revolutions per minute of the ball mill and *E* is the % amount of water added for wet grinding as defined in Table 4. The design matrix considering minimum, maximum and central value defined in Tables 4 and 5 for dry and wet grinding, respectively, was evaluated as per model. The experimental values were obtained by performing experiments, and the predicted values were calculated using Eqs. 6 and 7.

The experimental results were subjected to variance analysis (ANOVA) for both grinding methods. The results of ANOVA are shown in Table 5. The *F*-value of dry and wet grinding was 32.81 and 162.21, respectively. It was higher than 95% confidence level (*P*-value is less than 0.05). The values of *P*-values were acceptable for both models; it indicated that both models were convincing. Model terms or variables having *P*-values less than 0.05 are significant terms, on the other hand, variables having a *P*-value greater than 0.1 are not much significant for the model. Lack of fit in both cases was < 0.05, 0.012 for dry grinding and 0.04 for wet grinding, respectively. It is not significant in both cases. The values of regression coefficients are shown in Figure 1 for dry and wet grinding; the predicted values using Eqs. (6) and (7) and experimental values are in good agreement.

Table 3. Design matrix with coded & actual design parameters for dry grinding

Run No.	Coded				Uncoded				d_{80} exp	d_{80} pre
	A	*B* (g)	*C* (min)	*D* (rpm)	*A*	*B* (g)	*C* (min)	*D* (rpm)		
1	-1	-1	0	0	10	100	7	30	2.90	2.96
2	-1	1	0	0	10	200	7	30	2.94	2.89
3	1	-1	0	0	20	100	7	30	2.64	2.70
4	1	1	0	0	20	200	7	30	2.89	2.84
5	0	0	-1	-1	15	150	4	20	2.97	2.93
6	0	0	-1	1	15	150	4	40	2.90	2.91
7	0	0	1	-1	15	150	10	20	2.89	2.89
8	0	0	1	1	15	150	10	40	2.50	2.54
9	-1	0	0	-1	10	150	7	20	2.95	2.93
10	-1	0	0	1	10	150	7	40	2.82	2.84
11	1	0	0	-1	20	150	7	20	2.95	2.87
12	1	0	0	1	20	150	7	40	2.62	2.59
13	0	-1	-1	0	15	100	4	30	2.94	2.96
14	0	-1	1	0	15	100	10	30	2.79	2.71
15	0	1	-1	0	15	200	4	30	2.94	2.96
16	0	1	1	0	15	200	10	30	2.87	2.79
17	-1	0	-1	0	10	150	4	30	2.96	2.93
18	-1	0	1	0	10	150	10	30	2.77	2.80
19	1	0	-1	0	20	150	4	30	2.84	2.86
20	1	0	1	0	20	150	10	30	2.48	2.57
21	0	-1	0	-1	15	100	7	20	2.92	2.94
22	0	-1	0	1	15	100	7	40	2.85	2.78
23	0	1	0	-1	15	200	7	20	2.87	3.00
24	0	1	0	1	15	200	7	40	2.75	2.79
25	0	0	0	0	15	150	7	30	2.67	2.67
26	0	0	0	0	15	150	7	30	2.67	2.67
27	0	0	0	0	15	150	7	30	2.67	2.67

Table 4. Design matrix with coded & actual design parameters for wet grinding

Run No.	Coded					Uncoded					d_{80} exp	d_{80} pre
	A	*B* (g)	*C* (min)	*D* (rpm)	*E* (ml)	*A*	*B* (g)	*C* (min)	*D* (rpm)	*E* (ml)		
1	-1	-1	0	0	0	10	100	7	30	20	2.56	2.56
2	-1	1	0	0	0	10	200	7	30	40	2.85	2.83
3	1	-1	0	0	0	20	100	7	30	20	2.41	2.39
4	1	1	0	0	0	20	200	7	30	40	2.75	2.79
5	0	0	-1	-1	0	15	150	4	20	30	2.98	2.95
6	0	0	-1	1	0	15	150	4	40	30	2.32	2.35

7	0	0	1	-1	0	15	150	10	20	30	2.62	2.60
8	0	0	1	1	0	15	150	10	40	30	1.71	1.70
9	0	-1	0	0	-1	15	100	7	30	10	2.05	2.05
10	0	-1	0	0	1	15	100	7	30	30	2.63	2.65
11	0	1	0	0	-1	15	200	7	30	20	2.51	2.49
12	0	1	0	0	1	15	200	7	30	60	2.72	2.74
13	-1	0	-1	0	0	10	150	4	30	30	3.02	3.05
14	-1	0	1	0	0	10	150	10	30	30	2	2.01
15	1	0	-1	0	0	20	150	4	30	30	2.43	2.41
16	1	0	1	0	0	20	150	10	30	30	2.42	2.45
17	0	0	0	-1	-1	15	150	7	20	15	2.84	2.89
18	0	0	0	-1	1	15	150	7	20	45	2.42	2.46
19	0	0	0	1	-1	15	150	7	40	15	1.14	1.16
20	0	0	0	1	1	15	150	7	40	45	2.61	2.68
21	0	-1	-1	0	0	15	100	4	30	20	2.62	2.67
22	0	-1	1	0	0	15	100	10	30	20	2.11	2.18
23	0	1	-1	0	0	15	200	4	30	40	2.83	3.01
24	0	1	1	0	0	15	200	10	30	40	2.65	2.51
25	-1	0	0	-1	0	10	150	7	20	30	2.88	2.95
26	-1	0	0	1	0	10	150	7	40	30	2.06	2.05
27	1	0	0	-1	0	20	150	7	20	30	2.78	2.70
28	1	0	0	1	0	20	150	7	40	30	2.16	2.10
29	0	0	-1	0	-1	15	150	4	30	15	2.43	2.39
30	0	0	-1	0	1	15	150	4	30	45	2.75	2.76
31	0	0	1	0	-1	15	150	10	30	15	1.78	1.72
32	0	0	1	0	1	15	150	10	30	45	2.42	2.44
33	-1	0	0	0	-1	10	150	7	30	15	2.3	2.28
34	-1	0	0	0	1	10	150	7	30	45	2.62	2.58
35	1	0	0	0	-1	20	150	7	30	15	1.95	1.93
36	1	0	0	0	1	20	150	7	30	45	2.75	2.72
37	0	-1	0	-1	0	15	100	7	20	20	2.81	2.86
38	0	-1	0	1	0	15	100	7	40	20	1.92	1.93
39	0	1	0	-1	0	15	200	7	20	40	2.98	3.02
40	0	1	0	1	0	15	200	7	40	40	2.42	2.44
41	0	0	0	0	0	15	150	7	30	30	2.33	2.33
42	0	0	0	0	0	15	150	7	30	30	2.33	2.33
43	0	0	0	0	0	15	150	7	30	30	2.33	2.33
44	0	0	0	0	0	15	150	7	30	30	2.33	2.33
45	0	0	0	0	0	15	150	7	30	30	2.33	2.33
46	0	0	0	0	0	15	150	7	30	30	2.33	2.33

Table 5 ANOVA analysis of dry and wet grinding

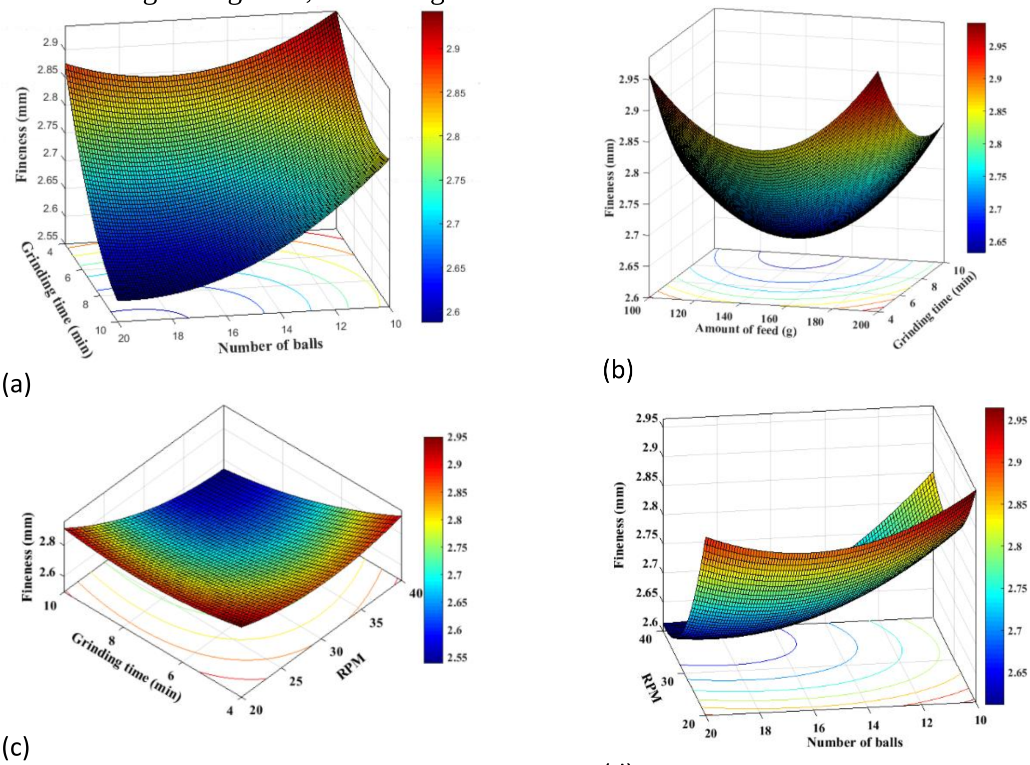
	Dry grinding				
Source	The sum of square distances (SS)	Mean squares	*F*-value	*P*-value	P_A =(SS/SS$_{total}$) %
Model	0.4736	0.0338	32.81	0.000	-
A	0.0118	0.0118	11.52	0.005	2.68
B	0.0608	0.0608	59.04	0.000	13.79
C	0.00035	0.00035	0.34	0.57	0.08
D	0.00375	0.0037	3.64	0.081	0.85
Square	0.0924	0.023	22.4	0.000	20.96
A*A	0.0202	0.0202	19.67	0.001	4.58
B*B	0.0805	0.0805	78.14	0.000	18.26
C*C	0.0163	0.0163	15.88	0.002	3.70
D*D	0.0377	0.0377	36.64	0.000	8.55
Interaction	0.0585	0.0097	9.47	0.001	13.27
A*B	0.0132	0.0132	12.82	0.004	2.99
A*C	0.0064	0.0064	6.21	0.028	1.45
A*D	0.0081	0.0081	7.85	0.016	1.84
B*C	0.002	0.0025	1.96	0.186	0.45
B*D	0.0016	0.0016	1.55	0.237	0.36
C*D	0.0272	0.027	26.4	0.000	6.17
Lack-of-fit	0.0123	0.0012			
Pure Error	0	0			
Total	0.4408				
	Wet grinding				
Source	Adj SS	Adj MS	F	P	P_A =(SS/SS$_{total}$) %
Model	6.344	0.3172	162.21	0.000	-
A	0.229	0.2299	117.56	0.000	5.05
B	0.033	0.0339	17.37	0.000	0.73
C	0.171	0.1713	87.62	0.000	3.77
D	0.0463	0.0463	23.68	0.000	1.02
E	0.161	0.161	82.33	0.000	3.55
Square	0.6127	0.1225	62.66	0.000	13.51
A*A	0.1199	0.1199	61.35	0.000	2.64
B*B	0.3206	0.3205	163.92	0.000	7.07
C*C	0.0186	0.0186	9.54	0.005	0.41
D*D	0.00078	0.00078	0.4	0.533	0.02
E*E	0.0256	0.0256	13.12	0.001	0.56
Interaction	1.3432	0.1343	68.68	0.000	29.62
A*B	0.0126	0.0126	6.45	0.018	0.28
A*C	0.255	0.255	130.39	0.000	5.62
A*D	0.01	0.01	5.11	0.033	0.22
A*E	0.0576	0.0576	29.45	0.000	1.27
B*C	0.0023	0.00235	1.2	0.283	0.05

B*D	0.1496	0.1496	76.54	0.000	3.30
B*E	0.0313	0.0313	16.03	0.000	0.69
C*D	0.0156	0.0156	7.99	0.009	0.34
C*E	0.0256	0.0256	13.09	0.001	0.56
D*E	0.893	0.893	456.61	0.000	19.69
Lack-of-fit	0.0488	0.0024			
Pure Error	0	0			
Total	4.53				

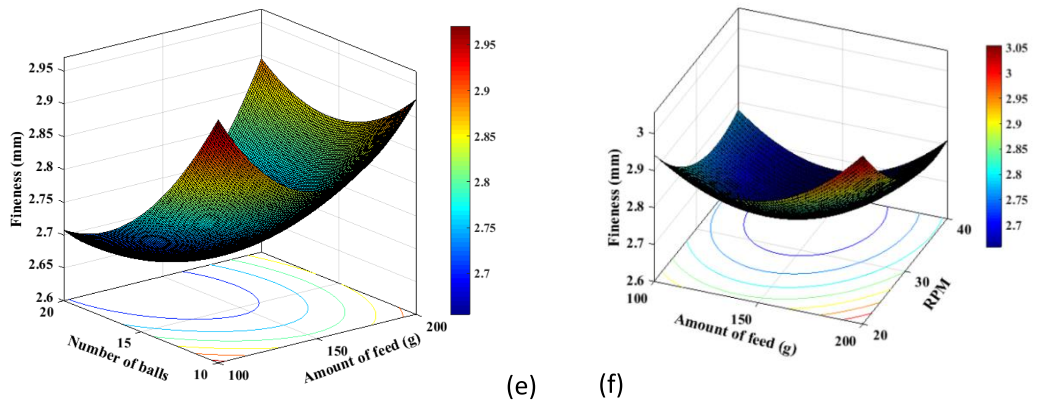
Effect of variables on fineness for dry grinding

In order to understand the interaction effect of operating parameters on the d_{80} the results are shown as 3D surface plots in Figures 1 (a - f). Since the model has four independent parameters, one factor was kept constant at the centre level for each plot.

Figure 1 (a) shows the effect of grinding time and number of balls on fineness of coal particles. At constant grinding time, decreasing number of balls has a reversed trend on fineness; similar effect has also observed for the decreasing grinding time for constant number of balls. Figure 1 (b) indicates the effect of grinding time and amount of feed on fineness. For constant grinding time, increasing or decreasing amount of feed exhibits coarser particle size and a minimum particle size at the centre value. It implies that too low or too high loading of feed will not result in fine particles. It can be explained by the feed to ball ratio in the ball mill. Bu *et al.* [6] have used this ratio in the range of 0.88 - 0.9 and observed an optimum fineness and breakage of particles. In the present experiments, 0.86 had been used as the feed to ball ratio. It is reported that the breakage rate of quartz and chlorite both were observed increasing with increase in feed size up to 0.5 mm and reduced when further increasing the size.



(a) (b) (c) (d)

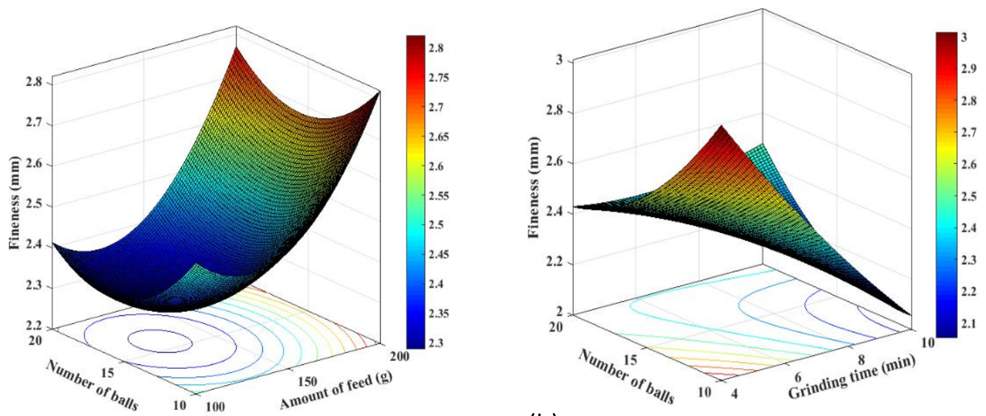


(e) (f)

Figure 1 (a-f) 3D plots of all four parameters combination effect on response as fineness of coal.

Figure 1 (c) shows the effect of grinding time and revolutions per minute (rpm) of the ball mill on the fineness of coal particles. Grinding time does not affect much at a constant speed of revolution of the ball mill. On the other side, increasing speed of the ball mill at constant grinding time does not facilitate producing fine particles. Figure 1 (d) shows the effect of rpm of mill speed and number of balls with fineness. In this plot, it can be seen that the increasing ball mill speed at a constant number of balls, the particle size decreases. Effect of number of balls on fineness is similar to Figure 1 (a) and fineness increases with increasing number of balls. Coal is used in stirred for variable ball mill speed and it is observed that increasing speed from 360 to 1440 rpm reduced the particles from mm to µm. However, energy consumption was high at 1440 rpm speed, therefore it was expected to use an optimum speed of the ball mill.

Figure 1 (e) shows the effect of the amount of feed and number of balls on the fineness or d_{80} of particles. Feed amount shows the similar effect as in Figure 1 (b) that at a constant number of balls, too low or too high feed will yield less breakage of particles and fewer fine particles. At the same instance, with constant feed amount, fine particles increased at the centre and decreased at minimum and maximum number of balls. Figure 1 (f) shows the effect of the amount of feed and rpm of the ball mill on fineness. The ball mill speed at higher and lower values yields coarser particle size. However, at the centre is the minimum particle size. The effect of ball mill speed is opposite to that in Figure 1 (d), this may be due to the interaction of the different parameters in both cases. However, the amount of feed has a similar effect on fineness as in Figures 1 (b and e).



(a) (b)

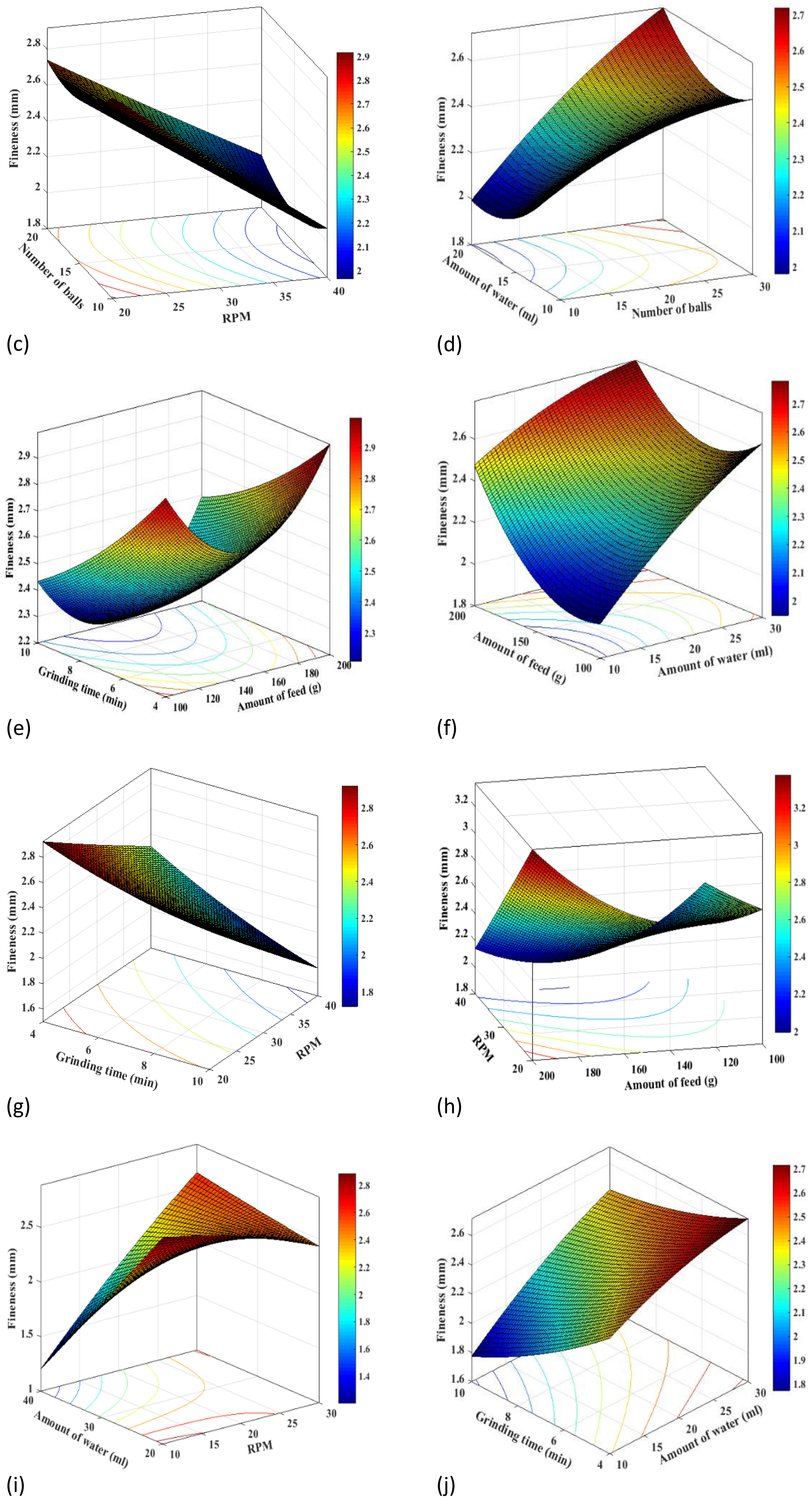


Figure 2 (a - j) 3D plots of wet grinding independent parameters with their response as fineness of coal.

Effect of variables on fineness for wet grinding

In these experiments, five independent parameters were taken to model the system as in Eq. (7). Water as the fifth parameter was added to increase the pulp density. Accordingly, a matrix as in Table 6 was prepared. Figure 2 (a) shows the effect of the number of balls and amount of feed on the fineness of coal particles. It can be seen that at a constant number of balls, the particle size increases with increasing amount of feed. It is known from the literature that slurry density has a major effect on grinding and fineness. It can be seen that at a number of balls for a constant feed, a minimum particle size was observed at the centre and increasing or decreasing the number of balls reduces the fineness of the particles. The similar behaviour was observed in the dry grinding.

Figure 2 (b) shows the effect of a number of balls with grinding time on fineness. Number of balls has a similar effect as in Figure 2 (a), however, for a constant number of balls an increase in grinding time is almost ineffective to fineness of particles. Figures 2 (c) and 2 (d) depict the effect of the number of balls with ball mill speed and amount of water added, respectively. Effect of number of balls with constant ball speed has not much significance on fineness. However, on increasing the rpm of the ball mill at a constant number of balls, fineness increases. On the other side of the constant number of balls the increasing amount of water will produce minimum particle size at the centre value than the highest and lowest values.

Figures 2 (e) and 2 (f) show the effect of the amount of feed in grinding time, and of the amount of water on fineness, respectively. Amount of feed shows a similar effect on fineness, which is a minimum at the centre and increasing size while reaching a high and low value of feed with constant grinding time and amount of water in both plots. However, grinding time and amount of water at constant feed reveals that increasing both parameters results in fine particles.

Figures 2 (g), 2 (h) and 2 (i) illustrate the interaction of rpm of the ball mill with grinding time, amount of feed and amount of water. Increasing rpm of the mill decreases the particle size for constant grinding time and amount of feed, however, reverse trends were observed on fineness for mill speed with a constant amount of water. Figures 2 (g) and 2 (j) show that increasing grinding time will result in finer particles. Increasing amount of water with constant grinding time and mill speed in Figure 2 (i) and (j) result in coarse particles.

Optimum conditions for dry and wet grinding

Table 6 shows the optimized conditions by the model equation, three experiments were performed and the error was calculated. The error was observed ±5 %. The fineness can also be compared in the table, the same size of feed was taken in both types of grinding and 0.526 mm and 2.411 mm of product size were predicted for wet and dry grinding, respectively; eventually, experiments confirmed the prediction. It is to be noted that for the same experiment dry grinding requires 20 balls and wet grinding needed only 13 balls and much smaller particles were yielded with wet grinding.

Table 6. Validation of experiments for dry and wet grinding for predicted model equations developed

Dry Grinding							
Run no	*A* (numbers)	*B* (g)	*C* (min)	*D* (rpm)	d_{80} predicted (mm)		d_{80} experimental (mm)
1	20	133.06	10	40	2.411		2.36
2	20	133.06	10	40	2.411		2.32
3	20	133.06	10	40	2.411		2.35
Wet Grinding							
Run no	*A* (numbers)	*B* (g)	*C* (min)	*D* (rpm)	*E* (ml)	d_{80} predicted (mm)	d_{80} experimental (mm)
1	12.9 ≈ 13	152.525	10	40	10% of feed = 15.2	0.526	0.510
2	12.9 ≈ 13	152.525	10	40	10% of feed = 15.2	0.526	0.535
3	12.9 ≈ 13	152.525	10	40	10% of feed = 15.2	0.526	0.515

CONCLUSIONS

In the present work, the three-level factorial Box–Behnken experimental design models were investigated for wet and dry grinding of coal for five variables, namely: grinding time, ball charge, amount of feed, amount of water, and rotational speed used for dry and wet grinding. These were all possible parameters which influenced the fineness of coal particles.

It can be concluded from the results that all parameters have a significant effect on fine particles production by grinding. The model equation with RSM and the *P*-value and *F*-value indicated a good agreement between predicted and experimental values. The correlation coefficient (R^2) for dry grinding was 0.97 and for wet grinding was 0.98.

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