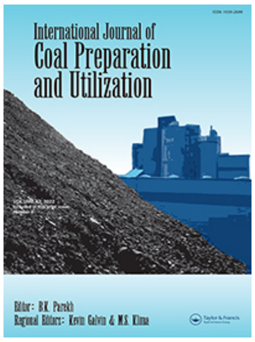

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Recovery of clean coking coal from difficult-to-wash low volatile coking coal fines of Jharia coalfield by multi gravity separator

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ABSTRACT

Multi-gravity separator (MGS) is a centrifugal gravity separator deployed for beneficiation of fine particles with relatively low concentration. It is for the first time that a statistical tool was engaged to evaluate effects of the most influencing process variables and their actual impact upon the performance of MGS with respect to its potential to clean the difficult-to-wash low volatile coking (LVC) coal fines. Characteristics of LVC coal sample were analyzed and discussed in terms of physical properties, petrographic composition, washability, XRD and SEM analysis. Three different feed sizes such as – 500 µm, – 250 µm and – 150 µm were used for assessing the separation mechanism and efficacy of MGS along with three different process variables such as drum speed, shaking amplitude and wash water rate to study and ascertain the most efficient experimental design for obtaining optimal result. Results revealed that drum speed and feed size turned out to be most significant parameters for reduction of ash concentration. In design of experiments, clean coal ash, combustible recovery and separation efficiency were considered as response functions. Material balance for MGS unraveled that about 74% clean coal produced with 10% ash reduction from the feed ash of 32.8% could be achieved in single stage, in optimized process conditions.

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KEYWORDS
LVC coal; MGS; fine coal beneficiation; separation mechanism

Introduction

Coal is a nonrenewable naturally occurring solid fuel containing mineral matter in its formation. The use of coal in India has increased drastically for meeting the incremental requirement of modern high capacity coal mining industries. As a natural corollary, coal mining industries adopted highly mechanized technology for enhancing production efficacy leading to generation of huge quantity of fines comprising good quality coal. As otherwise it results in wastage of scarce commodity coal apart from impacting adversely the environment. Proper utilization of coking coal fines is imperative for its sustainability, because the available coking coal reserves in the country is around 10.7% out of 326.5 Bt of total coal reserves as on 1 April Geological Survey of India (GSI) 2019). In addition, fast depletion of good-quality coking coal coupled with generation of unused coking coal fines results in high dependency on import of coking coals. To overcome these difficulties, utilization of

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accessible inferior grade coking coals and its fines has been necessitated by deploying advanced beneficiation techniques (Jyoti et al. 2015). India has moderate reserves of low volatile coking coals, which is more than 50% of the coking coal reserves available. These coals exhibit difficult washability characteristics due to the presence of high percentage of ash, more near gravity material and also poor liberation characteristics in nature (Charan et al. 2018; Chattopadhyaya and Charan 2021). However, extensive research has become imperative for proper utilization of these coal fines through cost-effective beneficiation methods, to recover good-quality clean coals, which not only improves proper and efficient utilization of coking coals but also minimizes the ever increasing dependency on import of coking coals.

Established beneficiation techniques for treatment of coal fines are flotation, gravity separation and also combination of both methods over the years (Bhattacharya 2009; Bhattacharya et al. 2016; Chaudhuri et al. 2014; Dey and Pani 2012). However, these methods are relatively not much useful for processing fine particle due to inefficient separation performance, loss of fine clean coal particles in tailing and poor process recovery (Chaurasia, Sahu, and Nikkam 2018; Majumder, Bhoi, and Barnwal 2007). Surface property-based beneficiation processes i.e froth floatation and oil agglomeration lacks the desired cleaning efficacy with respect to fine particles apart from being inadequate in its selective separation ability in feed coal containing large quantity of unliberated fine particles (Luttrell, Honaker, and Phillips 1995). In order to overcome these inherent constraints in outdated experimental model, there has been significant improvement in designing experimental model for treatment of fines using new generation enhanced gravity techniques such as Falcon concentrator, multi-gravity separator (MGS), Knelson concentrator and Kelsey jig, etc. These methods deploy centrifugal force to enhance the relative settling velocity of the fine particles thereby improving the particles separation (Roy 2009, Can, Özgen and Sabah 2010a; Özgen et al. 2011). Hence, they are also called as centrifugal separators. Honaker (1998) reported that enhanced gravity separators have the capability to treat particles finer than 212 μm effectively which are traditionally beneficiated in flotation process. A comprehensive review was undertaken on the developments of new advanced gravity concentrators for beneficiation to recover the fine particles (Das and Sarkar 2018; Sarkar, Sekhar, and Das 2007). It has been observed from the in-depth critical review (Wang et al. 2018) that there exist limitations in beneficiation techniques currently deployed for ultra-fine coal particles and the forthcoming developments for recovering the ultrafine coal particles. It stands critically established that enhanced gravity concentration is highly successful in efficiently separating the finer feed-size vis-à-vis by deploying the conventional methodology (Nayak, Jena, and Mandre 2021). A fine coal cleaning circuit was developed and demonstrated using Falcon concentrator especially for cleaning high sulfur coal and its suitability for −600 + 45 μm size fraction particles was evaluated (Mohanty, Samal, and Palit 2008). Reflux Classifier, which is a combination application comprising of three varying methodologies, namely, the liquid fluidized bed, autogenous dense medium and lamella settle, which was adopted for the beneficiation of fine coal (Kopparthi et al. 2019). In recent development in experimental model, gravity separators such as Falcon concentrator have been found to be efficient for beneficiation of difficult-to-wash LVC coal fines for recovering clean coal (Andavarapu, Vidyadhar, and Prasad 2021). Very recently, a comprehensive review has been published on current developments in beneficiation methods of coal fines and ultra-fines (Ramudzwagi, Tshiongo-Makgwe, and Nheta 2020).

The MGS is the most well-known centrifugal enhanced gravity separator that has been designed and developed for the beneficiation of fine and ultra-fine particles. Many researchers have done a commendable investigation on the applications of MGS for fine coal beneficiation (Chaurasia, Sahu, and Nikkam 2018; Fitzpatrick et al. 2018; Menendez et al. 2007; Özbakir, Koltka, and Sabah 2017; Özgen et al. 2009; Venkatraman et al. 1995). The application of MGS for processing Turkey lignite coal was studied and found to be successful in optimizing the process variables using response surface methodology in combination with central composite rotatable design (Aslan, 2007). Extremely difficult to wash tailing pond coal having high percentage of ultra-fine particles was treated in MGS with prior desliming. The results as obtained revealed that it is possible to produce clean coal of 20.6% ash with combustible material recovery of 35.3% (Menendez et al. 2007). Beneficiation of ultra-fine hard coal from coal preparation plant tailing was studied using desliming by hydrocyclone followed by MGS. It was noted that clean coal containing 6.98% ash was obtained with recovery of 61.73% from the deslimed feed having 28.41% ash (Özgen et al. 2009). Deploying MGS, it is possible to wash the fine lignite coal pond tailings with prior desliming classification. Investigation through this process revealed that ash concentration effectively reduced to 24.5% with 36.16% yield from the feed ash of 54.82% (Özbakir, Koltka, and Sabah 2017). Recently, efficacy and utility of MGS for beneficiation of coal fines were studied with respect to achieving optimization of key process variables of MGS using Box-Behnken Design method (Chaurasia and Nikkam 2017). In addition, the compilation of MGS in terms of design and feed parameters along with outcome as achieved, undertaken by several investigators is shown in Table 1. It was observed that MGS has the potential to beneficiate different varieties of fines and ultra-fine coals. However, most of their studies have been evaluated for optimization of some process parameters and none of the investigator has studied the effect of different feed sizes on MGS performance. The authors are not aware of any articles on MGS treating low volatile coking coals for recovering clean coal, till date.

Hence, a detailed investigation is required for beneficiation of LVC coal using MGS. Considering the significance of MGS, the main objective of the present investigation is to evaluate the feasibility of beneficiation by MGS for recovering clean coal from the Indian low volatile coking coal. Further in this article, experimental as well as statistical attempt has been made to understand the effect of four most influencing process parameters of MGS such as drum speed, shaking amplitude, wash water rate and feed size on its response functions such as clean coal ash, combustible recovery and separation efficiency for producing metallurgical grade coking coal.

Multi Gravity Separator

MGS is one of the centrifugal water-based enhanced gravity separator, which is specifically developed for treatment of fine and ultra-fine particles in the mineral processing industry. The working principle of the MGS is available in several literatures (Bandopadhyay 2000; Goktepe 2005; Tripathy et al. 2012) demonstrating that it is similar to a rotating horizontal surface of the traditional shaking table into a drum. Gravitational force on the particles, amplified many times than the normal gravity due to the rotated flowing film of water layer along with particles across the drum inner surface. Figure 1 shows the schematic diagram of MGS. It consists of a slightly tapered

Table 1. Compilation of evaluated MGS operational parameters for fine coal treatment.

MGS Variables studied		Chaurasia, Sahu, and Nikkam (2018)	Özbakir, Koltka, and Sabah (2017)	Özgen et al. (2011)	Özgen et al. (2009)	Majumder, Bhoi, and Barnwal (2007)
Feed parameters	Material	Coal	Coal	Coal	Coal	Coal
	Size (µm)	−75	−500	−500	−600	−500
	Flowrate (l/min)	1	1	1–3	1–5	-
	Solids concentration (%)	10	15	10–20	10–25	10–30
	Ash content (%)	33.5	42.6	45.9	19.6	24.6
Design parameters	Drum speed (rpm)	120–280	225	170–229	170–229	240–280
	Drum tilt angle (°)	3–5	4	0–4	0–4	1–2
	Shake amplitude (mm)	15	20	10–20	10–20	12.7–25.4
	Shake frequency (cps)	4–5.7	4.9	4.9	4.9	4–5.7
	Wash water rate (l/min)	1	5	1–5	1–5	1–2
Outcome	Ash content (%)	19.4	24.2	22.8	6.98	14.7
	Recovery (%)	72.7	45.6	49.3	61.7	-

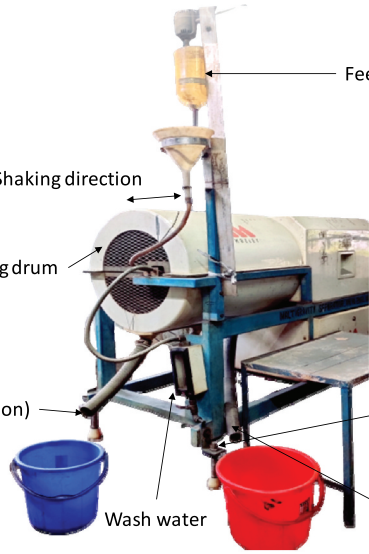

Figure 1. Schematic diagram of C-900 model Mozley Multi Gravity Separator.

open-ended drum with the dimensions of 60 cm length and 50 cm diameter. The drum rotating with a variable speed in the range of 140–300 rpm in clockwise direction enables generation of gravitational force on the drum surface in the range of 6–24 g. A longitudinal axial shake with an amplitude varying between 12 and 25 mm and shaking frequency varying between 2 and 6 cps is superimposed on the rotation of the drum. A scraper assembly is provided inside the drum, which rotates slightly faster than the rotating drum in the same direction for scraping the settled particles and at the same time they are subjected to counter-current washing of the particles before discharge. The movement of the particles and water inside the drum is controlled by the tilt angle (drum inclination) of the MGS through which particles residence time depends. The performance of the MGS is controlled by a number of design and process parameters which can be utilized to attain optimum operational conditions in separation of desired particles from the finely ground ore and upgradation of product grade.

Feed slurry is introduced along the inner surface of the drum via mesh ring to minimize the feed turbulence impact. Wash water is added through similar mesh ring near heavier particles at discharge end to clean the entrained lighter particles. During continuous feeding, the slurry follows a spiraling pattern on the rotating drum surface leading to generating centrifugal force in the revolving slurry flowing film. The lighter particles along with large amount of wash water flows to the far end of the drum, whereas heavier particles pinned to the surface of the drum are discharged by rotating scrapers toward front end of the drum. The application of MGS technology for the beneficiation of various minerals includes tin, tungsten, chromite, tantalum, celestite, wolfamite, coal and gold (Bhaskar et al. 1999). Process parameters that impact the performance of the MGS comprises of variables namely, drum speed, wash water, tilt angle, shake amplitude, shake frequency, feed pulp density, feed flow rate and feed size distribution.

Experimental

Feed Material and Its Characterization

LVC coal sample used in the present study was collected from Eastern region of Jharia coal fields containing maximum size of about 50 mm. This coal field is India's major prime coking coal depository situated in the Damodar Valley coal belt covering an area of about 458 sq km (Chandra 1992; Saikia and Sarkar 2013). The Jharia basin belongs to lower Gondwana group of Permian age consisting of Talchir, Barakar, Barren measures and Raniganj formations. Several geological features such as down-faulting, high-angle normal faults of enchelon type, inter-basinal gravity faults, dolerite dykes and mica-peridotite dykes, sills are associated with coal seams (Chandra 1992). The Jharia basin is unconformably overlying the Archean basement. The as-received coal sample from Jharia Basin was crushed to below 1 mm size through the combined closed circuit of jaw crusher followed by roll crusher for further size reduction. The sample was subdivided using coning and quartering method to obtain representative sample, which was used for detailed characterization studies while the remaining sample was bagged for carrying out the experimental work.

Detailed qualitative and quantitative techniques such as particle size distribution, size wise ash analysis, proximate analysis, ultimate analysis, chemical analysis, SEM, XRD and sink-float tests were carried out to assess the characterization of LVC coal sample. Particle size analysis of the sample was carried out in laboratory-scale sieve shaker with wet method and its size distribution is shown in Fig. 2. From the graph, it was noticed that D_{80} size of the sample is about 485 µm however around 50% of the sample was observed to be below 255 µm. The proximate analysis was determined using Coal Analyzer by air-dry basis presented in Table 2. It was observed that the sample contained 32.8% ash with volatile matter of about 16.7% and the remaining constituents have been shown in the Table 2. The ultimate analysis of the coal was determined by CHNS analyzer which revealed that the sample has 61.5% carbon followed by 3.4% H, 1.3% N and 0.5% of sulfur content. The

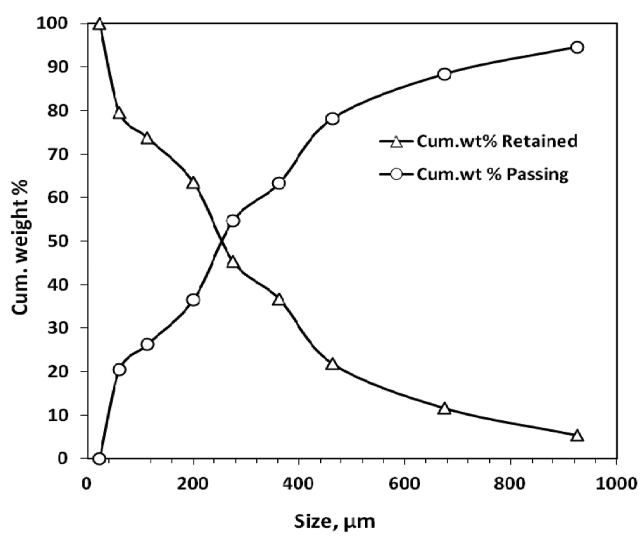

Figure 2. Particle size distribution & D_{80} size of the low volatile coking coal head sample.

Table 2. Physical characterization of LVC coal sample.

Proximate Analysis		Ultimate analysis	
Constituents	%	Composition	%
Moisture	0.84	Carbon	61.48
Volatile matter	16.72	Nitrogen	1.32
Ash content	32.81	Hydrogen	3.36
Fixed Carbon	49.63	Sulfur	0.51
Chemical Analysis		Petrographic analysis	
Radicals	%	Macerals	Vol. %
SiO_2	63.82	Vitrinite	40.21
Al_2O_3	21.02	Liptinite	1.52
Fe_2O_3	8.83	Inertinite	26.63
MgO	0.4	Mineral matter	31.64
CaO	0.55	Reflectance	1.14
Na_2O	0.28	**Gross calorific value**	
K_2O	1.06		
TiO_2	1.61	GCV, kcal/kg	5794.82
P_2O_5	0.73		
MnO	0.27		

heating value of the sample measured in GCV was found to be 5794 Kcal/kg. The chemical composition of the sample assays 63.8% SiO_2, 21% Al_2O_3, 8.8% Fe_2O_3 and other minor phases are mentioned in the Table 2.

Detailed coal petrographic studies were conducted using Advanced Polarizing Microscope (Leica DM4500, Germany) on polished coal sample, wherein it was observed that the sample contained 31.4% of mineral matter along with various maceral groups. Vitrinite and inertinite are the major macerals followed by minor amount of liptinite maceral. The reflectance (Ro) of the coal was found to be 1.15%, which means coal is highly matured and this is likely the reason for the low content of volatile matter. Mineralogical microanalysis studies were performed using Scanning Electron Microscopy (SEM) connected with EDS micro-analyzer to measure the textural characteristics of the head sample. The SEM analysis represents the presence and textural features of the carbon phase along with predominant minerals such as quartz, kaolinite and muscovite minerals, shown in Fig. 3. It also shows that the interlocking particles of quartz mineral with carbon phase is attributable to the poor liberation characteristics of the coal sample which poses difficulty in beneficiation process to recover the clean coal. The XRD study was performed to identify the various mineral phases present in the ash portion of the head coal sample using D8

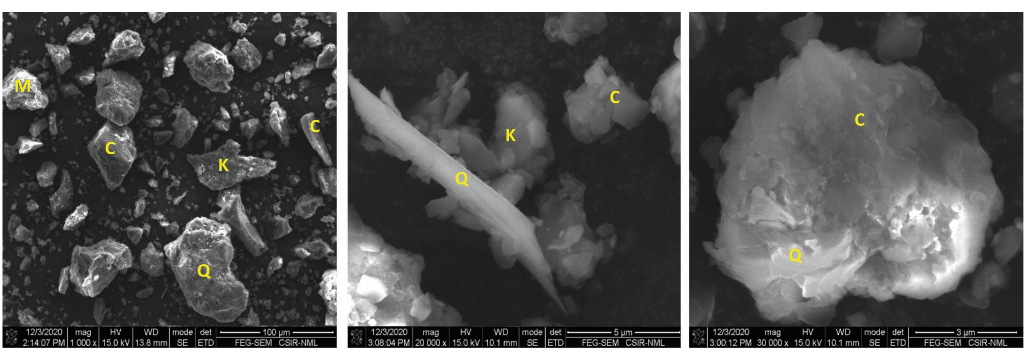

Figure 3. FEG-SEM images of LVC coal sample. (C: Carbon, M: Muscovite, K: Kaolinite, Q: Quartz).

Discover diffractometer (Bruker, Germany). XRD diffractograms showed that the mineral phase peaks comprising mainly kaolinite (K), muscovite (Ms), apatite (Ap), siderite (S) and quartz (Q), shown in Fig. 4. It is observed that quartz is the dominating silica phase along with other mineral phases as unraveled from the chemical analysis.

Theoretically washing potentiality of the coal can be estimated through the standard group of washability curves, whereas Mayer's curve (M-curve) method was developed to replace all the washability curves into a single curve which is useful for predicting the ash and yield percentages of the products obtained from the separation method (Hamidreza, Esmaeil, and Abbas 2012). This curve was constructed by sink-float analysis using mixtures of heavy organic liquids for the head sample of below 1 mm size. Sink- float tests were carried out as prescribed by Indian standard procedure (IS 13810, 1993). Test products were analyzed to calculate the weight and ash percentages at each specific gravity in the range of 1.3 to 2.0. M-curve was constructed using sink-float data by plotting cumulative weight percentage of floats against M-point values. Table 3 represents the M-point values determination thereby M-curve was drawn as demonstrated in the Fig. 5. The graphical representation of M-curve plot was useful for estimation of clean coal yield at any desired level of ash content and is also most suitable and accurate method for the prediction of cleaning feasibility of the coal. Mayer curve plot shows that theoretically 74.5% of clean coal yield is achievable at level of 19% ash content. The overall sink-float data and M-curve implies that low volatile coking coal might be washable at finer size for recovering the clean coal with the desired grade of ash content.

Thorough characterization along with washability studies on LVC coal sample revealed that the cleaning potentiality of the sample was significantly feasible at size below 1 mm. Considering the sample characteristics and process feed size restriction, the coal sample was ground to three individual top sizes, namely, – 500 µm, – 250 µm and – 150 µm to estimate the effect of particle size. Each size fraction of the coal sample was subjected to beneficiation studies using MGS. Three feed samples were also subjected to size distribution as well as size wise ash distribution analysis and is presented in the Table 4. It was observed that ash percent of each feed size fractions were uniformly

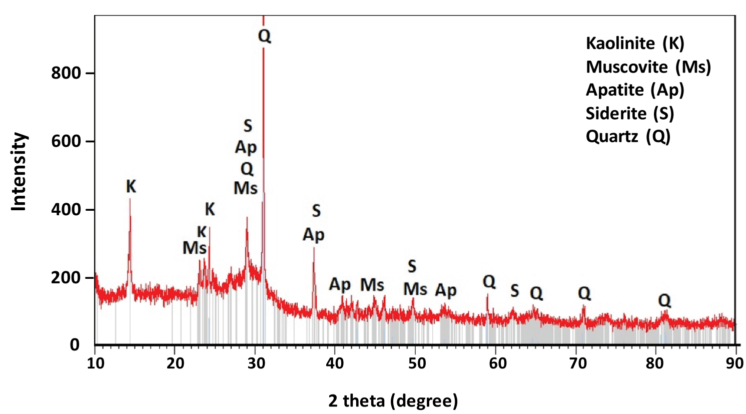

Figure 4. XRD diffractograms of LVC coal sample.

Table 3. Calculations for Mayer's curve construction of below 1 mm size LVC coal sample.

Specific gravity	Wt., (%)1	Ash (%) 2	Calculations for Mayer's-value			M- value6 = 4/ 100	Angle point
			Ash product 3 = 1 × 2	Cum. ash product 4 = ∑ (1 × 2)	Cum. wt% 5 = ∑ 1		
1.3	18.9	4.6	86.9	86.9	18.9	0.9	A
1.4	19.2	10.4	199.7	286.6	38.1	2.9	B
1.5	9.2	19.8	182.2	468.8	47.3	4.7	C
1.6	8.8	23.7	208.6	677.3	56.1	6.8	D
1.7	7.8	32.4	252.7	930.1	63.9	9.3	E
1.8	4.9	40.6	198.9	1129.0	68.8	11.3	F
1.9	2.3	47.3	108.8	1237.8	71.1	12.4	G
2.0	6.4	54.6	349.4	1587.2	77.5	15.9	H
2.0 Sink	22.5	76.4	1719.0	3306.2	100.0	33.1	I

distributed up to the size of 45 µm, whereas abrupt increase of ash content was noticed at size below 45 µm. The calculated average ash content of the LVC coal sample was about 32.7%.

Beneficiation

A bench/pilot scale C-900 model MGS (M/s Richard Mozley Ltd) was used in the present study and its experimental setup is schematically shown in Fig. 1. The design and operation variable significantly impact the performance of MGS on the given feed sample such as drum speed, drum tilt angle, shake amplitude, shake frequency, wash water rate, feed flow rate, feed pulp density and feed particle size. Whereas most impactful four out of these entire operating

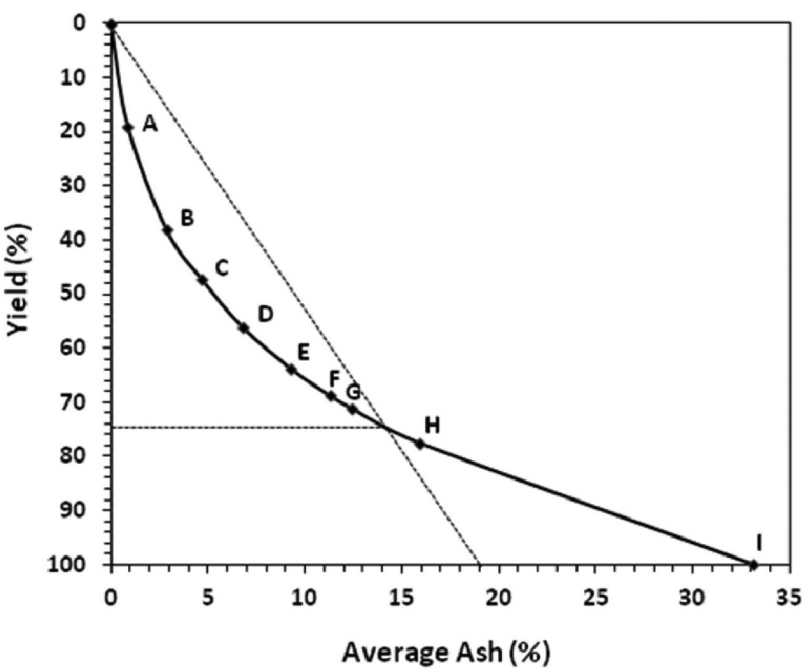

Figure 5. Mayer's curve for LVC Coal sample.

Table 4. Size distribution and size-wise ash distribution of feed sample for MGS.

	Feed: −500 µm		Feed: −250 µm		Feed: −150 µm	
Mesh size, µm	Wt., %	Ash, %	Wt., %	Ash, %	Wt., %	Ash, %
−500 + 425	11.6	30.8	-	-	-	-
−425 + 300	18.3	29.7	-	-	-	-
−300 + 250	9.7	33.4	-	-	-	-
−250 + 150	19.5	32.9	24.6	32.3	-	-
−150 + 75	12.1	32.6	26.1	32.5	25.8	31.7
−75 + 45	6.0	31.7	14.8	30.6	19.9	30.4
−45	22.7	35.8	34.5	34.4	54.3	33.8
Total	100.0	32.7	100.0	32.8	100.0	32.6

variables as cited above were chosen for the present study. However, the remaining parameters were kept constant for all the experiments. The levels of the process variables of MGS were established based on the initial few exploratory studies. Statistical approach was used for designing the experiments in order to obtain the optimum performance of variables with minimum number of experiments. A total of 29 experiments were conducted using response surface methodology combined with three level Box-Behnken Design (BBD) method in order to study the effects of operating parameters to produce clean coking coal. Most influencing four process parameters namely feed size, drum speed, shaking amplitude and wash water rate were considered for the experimentation and coded as X_1, X_2, X_3 and X_4, respectively. The ranges of four process variable values used in the BBD method along with fixed variables values operated for the all experiments are illustrated in Table 5.

Feed sample for each experiment was prepared with 20% of solids by weight through stirrer fixed slurry tank for proper mixing of sample throughout the tests. Before introducing the slurry sample at the constant flowrate of 2.5 l/min, MGS equipment operated with adjusted process variables as provided in the design methodology adopted. After completion of slurry feeding, wash water flow is continued for further 2 minutes in the running condition of MGS. Due to the centrifugal force developed inside the rotating drum, stratified flowing film formed on the inner surface of the drum. As a result, denser particles continuously get drawn toward front end of the drum while lighter particles were discharged as clean coal through back end of the drum. At the steady state condition, both clean coal and tailing products were collected and then dried, weighed and analyzed for ash percentage. The same procedure repeated for the all experiments at the required levels of process variables.

The influence of MGS process variables on response functions such as clean coal ash content, combustible recovery and separation efficiency were analyzed and optimized using statistical tool i.e. Response Surface Methodology (RSM). It is a useful experimental design methodology for theoretical prediction purpose. The main objective of the RSM is to

Table 5. List of operational variables and levels studied on MGS.

		Levels of variables				
Operational parameters	Code	Low (−1)	Middle (0)	High (+1)	Fixed parameters	
Feed Size (µm)	X_1	−150	−250	−500	Flowrate (l/min)	2.5
Drum speed (rpm)	X_2	160	200	240	Solids (%)	20
Shake amplitude (mm)	X_3	10	15	20	Shake frequency (cps)	4.9
Wash water rate (l/min)	X_4	2	4	6	Drum tilt angle (°)	2

optimize the response surface that gets impacted and influenced by the operating variables. It also quantifies the relationship between the adjustable input parameters and the achieved response surfaces (Aslan 2007). The model equation of RSM for prediction of responses can be expressed as following:

$$y = \beta_0+\beta_1 x_1+\beta_2 x_2+\beta_3 x_3+\beta_{11} x_1{}^2+\beta_{22} x_2{}^2+\beta_{33} x_3{}^2+\beta_{12} x_1 x_2+\beta_{13} x_1 x_3+\beta_{23} x_2 x_3 \quad (1)$$

where y is the predicted response, x_1, x_2 and x_3 independent variables; β_0 is model constant; β_1, β_2 and β_3 are linear coefficients; β_{12}, β_{13} and β_{23} are cross-product coefficients and β_{11}, β_{22} and β_{33} are the quadratic coefficients.

The Box Behnken designed experimental plan has been considered for the present studies on LVC coal sample using MGS. The obtained experimental data was analyzed and compared with predicted data acquired by ANOVA using Design Expert Software package and discussed further.

Results and Discussion

Statistically designed, a set of 29 experiments has been conducted on MGS for beneficiating the low volatile coking coal and the obtained results are given in Table 6. It is observed from the experimental data; MGS is able to separate the undesirable mineral matter from the LVC coal for producing low ash clean coal through varying process conditions. The responses of MGC on LVC coal was evaluated in terms of ash content, combustible recovery and separation efficiency. It has been seen that ash reduction in concentrate was highly dependent on feed size, drum speed and wash water rate. However, varying shake amplitude influenced yield of clean coal at its higher level. The aim of the present investigation was to obtain the optimum levels of the process parameters at which lower content of ash can be achieved. It has been found from the results that, minimum ash of 22.3% with 51% combustible recovery was achieved in the concentrate at feed size −150 µm, 240 rpm drum speed, 15 mm shake amplitude and 4 lt/min wash water. It was also noticed that maximum separation efficiency in the range of 8–11.1% can be possible at the higher levels of drum speed. Further, effects of four chosen MGS process parameters and their interaction on the three responses can be better evaluated through model equations obtained from the RSM, Design Expert software.

Optimization of process parameters of MGS was performed by regression analysis through ANOVA (analysis of variance). The relationship between input process variables such as feed size (X_1), drum speed (X_2), shaking amplitude (X_3) and wash water rate (X_4) and the response functions in terms of clean coal ash (Y_1), combustible recovery (Y_2) and separation efficiency (Y_3) was obtained in the form of model equations as shown in equations 2, 3 and 4 below respectively. The variation of response functions as changing the levels of input process variables of MGS can be determined using these model equations.

$$\begin{aligned} Y_1 = {} & 24.41 + 0.27X_1 - 2.25X_2 + 0.35X_3 + 1.03X_4 + 1 \\ & .25X_1X_2 + 0.5X_3X_4 - 0.97X_2X_4 + 0.96X_1{}^2 + 0.68X_2{}^2 \end{aligned} \quad (2)$$

$$\begin{aligned} Y_2 = {} & 51.11 - 7.29X_1 - 8.94X_2 + 1.43X_3 + 4.47X_4 \\ & + 4.15X_1X_2 - 3.61X_2X_4 + 2.19X_1{}^2 + 2.16X_2{}^2 \end{aligned} \quad (3)$$

Table 6. BBD Experimental results of MGS along with process parameters.

	Level of process parameters				Responses observed			
Test No.	Feed size (μm)	Drum speed (rpm)	Shake amplitude (mm)	wash water rate (l/min)	Ash (%)	Yield (%)	Combustible recovery (%)	Separation efficiency (%)
1	−250	200	10	6	24.3	69.6	51.8	6.1
2	−250	200	20	2	23.4	64.3	45.9	7.3
3	−150	200	20	4	25.3	79.6	61.7	5.2
4	−250	200	15	4	24.1	68.2	50.1	6.5
5	−250	200	15	4	24.2	68.6	50.7	6.4
6	−250	160	15	2	25.4	71.1	55.3	4.5
7	−250	160	20	4	28.2	76.2	65.9	1.6
8	−250	200	20	6	26.5	72.2	58.5	3.2
9	−250	200	10	2	23.2	64.8	46.2	7.5
10	−250	160	10	4	27.6	74.8	63.0	2.2
11	−500	240	15	4	25.2	57.4	44.0	4.1
12	−250	200	15	4	24.1	68.4	50.5	6.4
13	−150	200	15	2	24.4	77.2	57.7	6.6
14	−500	200	20	4	26.2	60.1	48.2	2.9
15	−150	240	15	4	22.3	74.8	51.0	11.1
16	−250	240	15	6	23.0	64.4	45.3	8.0
17	−250	240	10	4	22.8	59.3	41.1	8.1
18	−150	160	15	4	28.6	83.2	72.5	1.6
19	−500	200	15	2	25.1	54.3	41.7	3.8
20	−250	240	20	4	23.1	65.4	46.1	8.1
21	−250	200	15	4	24.0	68.1	49.9	6.6
22	−150	200	10	4	25.2	79.2	61.1	5.4
23	−250	200	15	4	24.3	68.8	50.9	6.3
24	−500	200	15	6	26.8	62.6	51.5	2.4
25	−500	200	10	4	25.4	59.4	46.0	3.9
26	−250	240	15	2	22.6	62.1	42.8	8.7
27	−150	200	15	6	26.2	80.1	64.0	4.1
28	−500	160	15	4	26.5	60.2	48.9	2.6
29	−250	160	15	6	29.7	79.2	72.2	0.7

$$Y_3 = 5.78 - 1.19X_1 + 2.89X_2 - 0.4X_3 - 1.16X_4 - 2.01X_1X_2 + 0.81X_2X_4 - 0.69X_3X_4 - 1.31{X_1}^2 \quad (4)$$

An analysis of variance (reduced quadratic models) for three response functions (clean coal ash, combustible recovery and separation efficiency) has been evaluated by design expert software as shown in Table 7. The model with higher R^2 value of 0.9656 for the clean coal ash implies significant correlation between the process variables and clean coal ash content attained. R^2 values of other responses like combustible recovery and separation efficiency indicates that the models are a very good fit and found to be in reasonably good agreement with adjusted R^2 values respectively. The probability values (P-value) for each

Table 7. Analysis of variance (ANOVA) for three responses.

Quadratic Model	Ash	Combustible recovery	Separation efficiency
Sum of Square	95.42	2040.3	168.45
Mean square	10.6	255.03	21.06
R^2 -value	0.9656	0.9641	0.9504
Adj. R^2 -value	0.9494	0.9498	0.9306
P-value	<0.0001	<0.0001	<0.0001
F-value	59.34	67.18	47.95
Standard deviation	0.43	1.95	0.66
Lack of Fit	17.14	28.45	27.16

Table 8. Model term wise P-values of three responses.

	p-values of responses		
Model terms	Ash	Combustible recovery	Separation efficiency
X_1	0.0416	< 0.0001	< 0.0001
X_2	< 0.0001	< 0.0001	< 0.0001
X_3	0.0098	0.0196	0.00511
X_4	< 0.0001	< 0.0001	< 0.0001
X_1X_2	< 0.0001	0.0004	< 0.0001
X_2X_4	0.0002	0.0014	0.00240
X_3X_4	0.0288	-	0.0514
X_1^2	< 0.0001	0.0079	< 0.0001
X_2^2	0.0004	0.0087	-

developed quadratic models are less than 0.05 indicating that there is a strong correlation between the independent variables and responses as obtained. The model fissure value (f-value) provides the effects of the process variables and their interactions with response functions. The f-values of three models are 59.34, 67.18 and 47.95 implies the models are adequate and reliable with predicted values of the responses. Considering the lower p-values and higher f-values for the three models, revealed that there is a high level of response significance was achieved by the developed models. In regression analysis, coefficient of p-values determines the statistical relationship between the process variables and responses and their significance. The p-value of each term (variables and their functions) in the model equation were shown in Table 8. The p-values of each term that is less than the significant levels were considered in the final models for improving the model's precision.

The relationship between the actual experimental results and predicted values of the clean coal ash (%), combustible recovery (%) and separation efficiency (%) obtained from the regression models are assessed by R^2 value and shown in Fig. 6. As it can be seen from the graphs, R^2 values of 0.9656, 0.9652 and 0.9504 for three responses indicate that predicted values are more identical with experimental values. It is evident that derived regression models are adequate and reliable within the levels of chosen operating conditions. The effect of process variables on MGS performance for obtaining minimum ash content clean coal with maximum combustible recovery and separation efficiency were discussed further using 3D response surface plots.

Effect of Variables on Clean Coking Coal Ash

MGS performance on LVC coal was investigated by assessing the impact of process variables at different levels. Figure 7a shows the effect of drum speed (160–240 rpm) and wash water rate (2–6 l/min.) selecting mid-level of feed size and shaking amplitude on clean coal ash content. 3D surface plot indicates that higher rpm of drum speed improves the product with lower ash content, which means increased drum speed enhances the centrifugal forces on coal particles, thereby forming a compact bed of dense mineral particles around the inner drum surface while lighter coal particles get withdrawn along with major water portion through front end of drum. It is observed that, as the wash water rate increases, the clean coal ash also increases significantly due to raise in water flow rate that agitates the settled dense layer. Figure 7b shows the effect of feed size and drum speed with mid-level of wash water rate and shaking amplitude on ash content. It was acknowledged

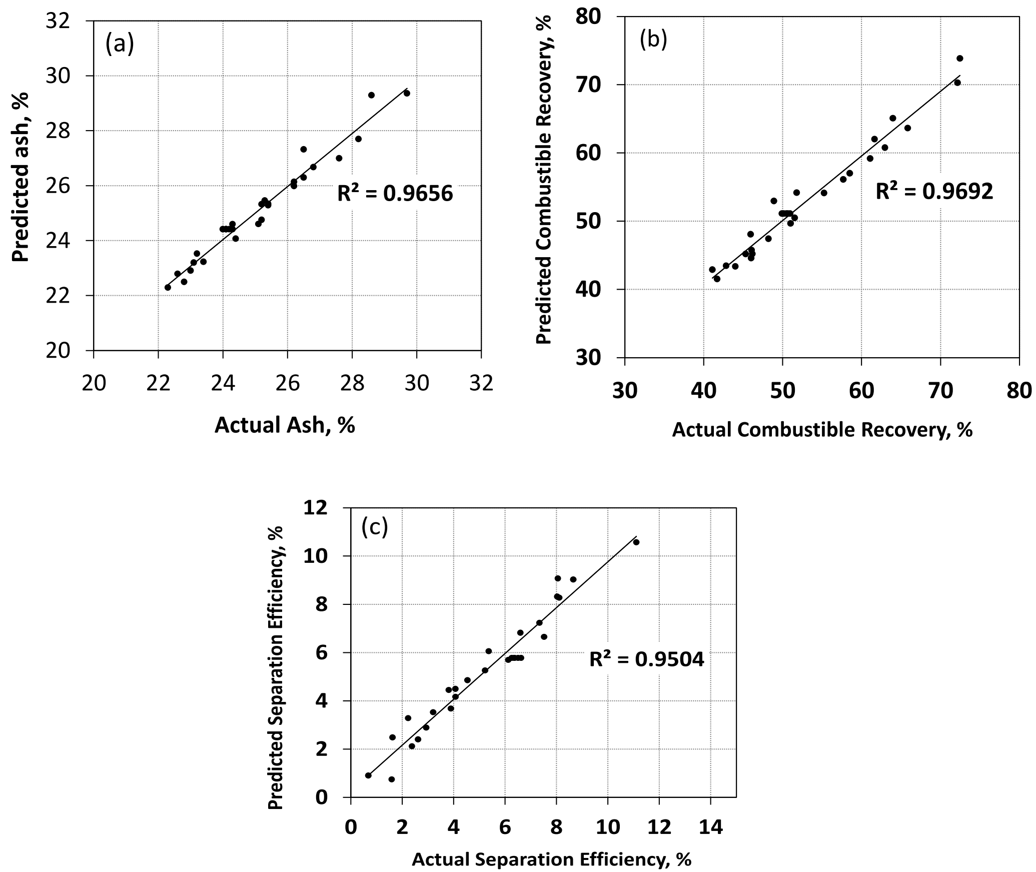

Figure 6. Relation between actual and predicted values of (a) Clean coal ash (b) Combustible recovery (c) Separation efficiency.

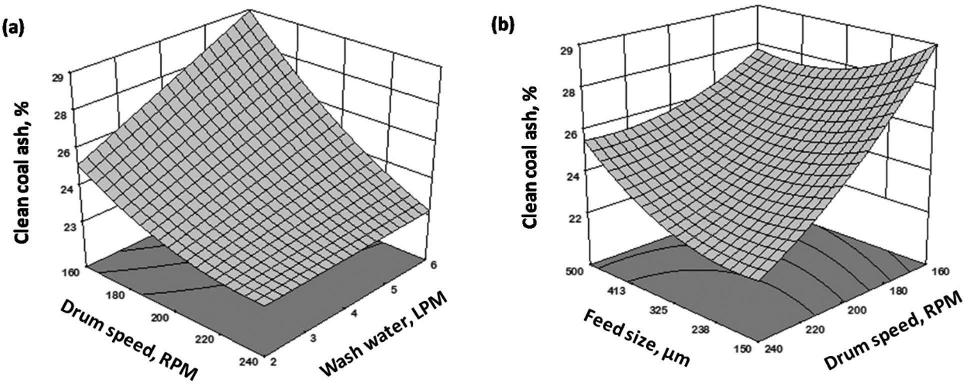

Figure 7. Surface plots showing the effect of (a) Drum speed and wash water (b) Feed size and drum speed on clean coal ash.

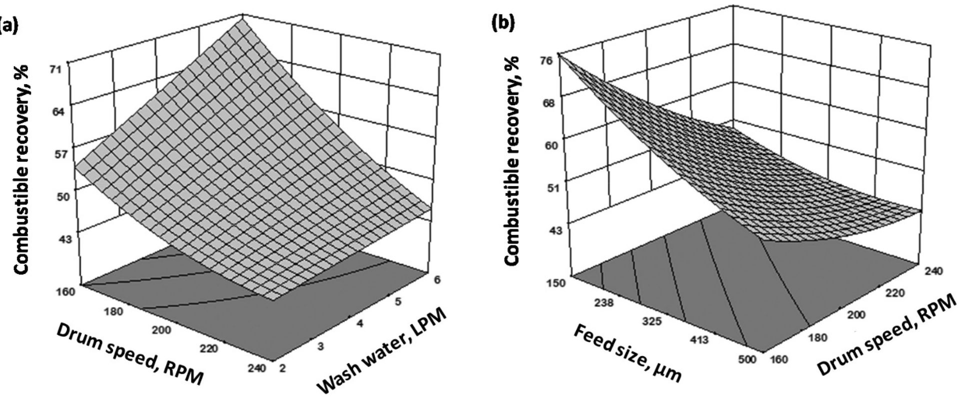

Figure 8. Surface plots showing the effect of (a) Drum speed and wash water (b) Feed size and drum speed on combustible recovery.

that ash content of concentrate decreased at lower feed size and higher drum speed. This is due to the fact that, decreased feed size contains more liberated coal particles and thereby increasing the separation of mineral matter when drum operates at higher revolution. It can be concluded that for reducing the ash content of the concentrate, MGS has to be operated with higher drum speed and lower feed size at which improved layer wise particles stratification occurring on the drum surface. Therefore, clean coal low ash particles at the upper layer, flow toward the concentrate.

Effect of Variables on Combustible Recovery

The predicted model for combustible recovery is expressed in 3D response surface plots in order to understand the effect of variables. Figure 8a shows the combined effect of drum speed and wash water rate at mid-levels of feed size and shaking amplitude on concentrate combustible recovery. With increase in wash water rate, a significant increase of combustible recovery was observed. High rate of washing can improve the cleaning of lighter coal particles toward drum front end i.e concentrate product. When the particles flow with increased flow of water it can enhance the separation of particles having various size and density. Figure 8b explains the effect of feed size and drum speed at the mid-level of other variables. The surface plots showed that maximum combustible recovery is possible at the lower levels of feed size and drum speed. It is also observed that finer particle size has more dominant impact for increased combustible recovery. It evidently occurs due to the finer particles of feed getting sufficiently liberated with mineral matter, thereby improving the MGS performance in terms of combustible recovery. Higher revolution of drum generates higher centrifugal forces on the feed material, which leads to increase of the grade of concentrate fraction. However, some quantity of lighter particles penetrate to dense particles of the bed thus eventually flowing through tailing end, as a result of reduction in combustible recovery.

Effect of Variables on Separation Efficiency

The effect of drum speed and wash water rate at mid-levels of shaking amplitude and feed size on MGS separation efficiency is shown in Fig. 9a. It was noticed from the surface plots that maximum separation efficiency was attained at higher rpm of drum revolution and lower rate of wash water. This can be explained that high centrifugal force acts on coal particles due to high revolution of drum which allows the separation of heavier mineral particles from the lighter coal particles, thereby enhancing the separation efficiency of MGS. It is also observed that, as the wash water rate increases, the separation efficiency of the concentrate fraction decreases slightly due to washing of stratified layers of the bed inside the drum which allows the re-mobilization of the upper layer that contain lighter clean coal particles, whereby the particles pass through tailing end thereby decreasing the efficiency of the MGS. Similarly, Fig. 9b represents the effect of feed size and drum speed at the mid-levels of other variables. It is observed that increased drum speed with decreased coal particle size collectively influence in enhancing the separation efficacy of MGS. This effect may be the reason that with the decrease in feed size, more liberated fine coal particles in the flow increased. As a result, separation of clean coal particles improved under the influence

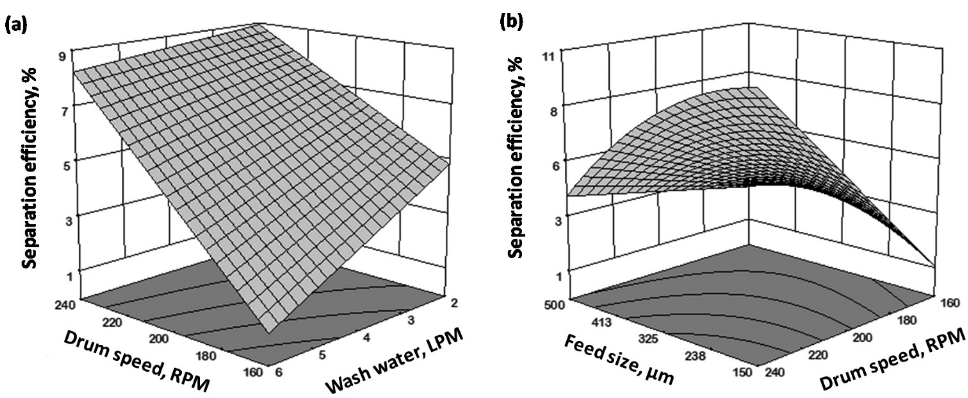

Figure 9. Surface plots showing the effect of (a) Drum speed and wash water (b) Feed size and drum speed on separation efficiency.

of centrifugal force inside the drum surface. As explained earlier, it is again justified that the beneficiation performance of MGS is highly efficient for separation of fine LVC coal particles.

Optimization Studies

Separation efficacy of any coal beneficiation equipment is usually assessed by the incremental responses such as concentrate product ash content, combustible recovery and separation efficiency. Accordingly, MGS performance was evaluated for the beneficiation of LVC coal sample. Optimization of MGS process variables was determined through the developed model equations using Design Expert software for achieving minimum ash content of clean coal product with maximum combustible recovery and separation efficiency. Optimization of each response is measured individually while keeping the other parameters within the specified range. The desirability value of 1.0 was obtained for each response thereby evidencing that the generated models for optimization of process variables is significant and adequate within the range of variables levels as shown in Fig. 10.

(i) Minimum ash content of 22.14% of clean coal product can be obtained from the feed ash of 32.7% at the following optimized level of the process variables.

Feed size: 185 µm

Drum speed: 238 rpm

Shaking amplitude: 10 mm

Wash water rate: 5 l/min.

(ii) Maximum combustible recovery of 72.8% of clean coal product can be achieved at the following optimized level of the process variables.

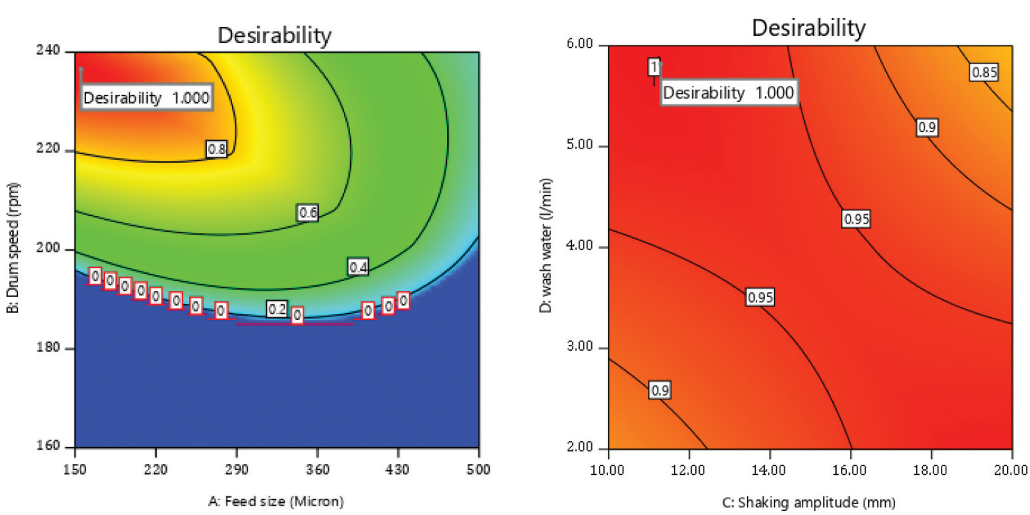

Figure 10. Optimum operating regime.

Feed size: 190 µm

Drum speed: 169 rpm

Shaking amplitude: 19 mm

Wash water rate: 5 l/min.

(iii) Similarly, Maximum separation efficiency of 11.2% can be achieved at the following optimized level of the process variables.

Feed size: 150 µm

Drum speed: 240 rpm

Shaking amplitude: 19 mm

Wash water rate: 2 l/min.

Further, optimized levels of process variables attained from the models were validated by the MGS experiments conducted in triplicate with LVC coal sample. Results indicated that LVC coal enrichment was almost equivalent with predicted values and hence suited to the obtained model equations.

Two Stage Cleaning

MGS is a most efficient beneficiation equipment for separation of fine coal particles. Under the optimized conditions of process variables of MGS, ash content of concentrate product was reduced to 22.3% with 74.3% of yield using 32.7% ash of LVC coal sample. Whereas desirable ash limit for making the metallurgical coke is about 18%. Therefore, re-cleaning of concentrate product obtained from the MGS is required in order to achieve the desired reduced level of ash content in clean coal. Two stage beneficiation of LVC coal using MGS was carried out at the same optimized process conditions and the results are mentioned in the Table 9. It was found that cleaner concentrate ash content reduced to 18.7% with overall 50.4% yield and 60.9% combustible recovery. In addition, Ash rejection in final tailing was observed to be 62.8% with 25.7% by weight. It can be observed from the table that two stage cleaning of LVC coal by MGC proved beneficial in meeting the required ash content specification of clean coal product for subsequent coke making process.

Table 9. Results of two stage Multi gravity separation.

Products	Wt., %	Wt. distribution, %	Ash, %	Combustible recovery, %
Rougher concentrate	74.28	-	22.26	85.8
Rougher tailing (Reject)	25.72	25.72	62.85	14.2
Cleaner concentrate	58.10	43.16	18.67	52.2
Cleaner tailing	41.90	31.12	27.30	33.6
Feed	100.00	100.00	32.70	100

Conclusion

The detailed characterization and beneficiation studies carried out on LVC coal from Jharia coalfields shows that using MGS effectively produced the desired low ash content coking coal. Mayer's curve predicts that about 19% ash content clean coal is theoretically achievable with 74.5% yield from the feed coal ash of 32.8%. Using the Box-Behnken design method for optimization of most impactful four process parameters of MGS for producing clean coking coal was evaluated. It was found in the study of the process variables, that higher rpm of drum speed coupled with lower feed particle size have a major influence on concentrate of ash content, while higher values of shaking amplitude and lower rate of wash water flow influences the combustible recovery. R^2, p and f- values obtained from the ANOVA for three response functions (clean coal ash, combustible recovery and separation efficiency) indicates that predicted models are impactful and adequate to the experimental results. It was observed from the statistically designed set of experimental results, clean coal product with low ash content of 22.3% is achievable at 74.3% yield under optimal operational conditions of MGS. Rougher concentrate fraction was re-treated in MGS and the required clean coal of 18.7% ash with 52.1% combustible recovery could be achieved. Based on the present studies, it can be concluded that use of MGS is effective for substantive reduction of ash content in difficult-to-wash LVC coal sample and the clean coking coal produced thereby can be utilized in process for coke making.

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Disclosure Statement

No potential conflict of interest was reported by the author(s).

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References

Andavarapu, M. R., A. Vidyadhar, and R. Prasad. 2021. Beneficiation of difficult-to-wash Indian low volatile coking coal fines by Falcon concentrator. *International Journal of Coal Preparation and Utilization*, in press. doi:10.1080/19392699.2021.1984902.

Aslan, N. 2007a. Application of response surface methodology and central composite rotatable design for modelling the influence of some operating variables of a multi-gravity separator for coal cleaning. *Fuel* 86:769–76. doi:10.1016/j.fuel.2006.10.020.

Bandopadhyay, A. 2000. Multi-gravity separator - an equipment for separation of fines. In *International symposium on processing of fines (2)*, eds. Bhattacharyya, P, Singh, R, Goswami, N. G, 81–92. Jamshedpur: CSIR-NML.

Bhaskar, K. U., J. P. Barnwal, T. C. Rao, and R. Venugopal. 1999. Multi gravity separator to enrich heavy minerals from a lead flotation concentrate. *Minerals & Metallurgical Processing* 16 (2):61–64. doi:10.1007/BF03402811.

Bhattacharya, S. 2009. Coking coal preparation in India: Problems and prospects. *The South African Coal Processing Society International Coal Conference*, Gauteng, South Africa, September 08.
Bhattacharya, S., D. Jyoti, L. Sahu, S. Dey, and H. Singh. 2016. Flotation of Low Volatile Coking Coal Fines. *Transactions of the Indian Institute of Metals* 70 (2):421–32. doi:10.1007/s12666-016-0996-3.
Can, M. F., S. Ozgen, and E. Sabah. 2010a. A study to recover coal from Turkish lignite fine coal tailings: Comparison of falcon concentrator and multi gravity separator (MGS). *Proceedings of 27th International Pittsburgh Coal Conference*, Istanbul, Turkey, 1682–97, October 11-14.
Can, M. F., S. Ozgen, and E. Sabah. 2010b. Studies of a Multi gravity separator (MGS) to produce clean coal from Turkish lignite and hard coal fine tailings. *Proceedings of 27th International Pittsburgh Coal Conference,* Istanbul, Turkey, October 11-14.
Chandra, D. 1992. *Jharia Coalfield*. Bangalore: Geological Society of India.
Charan, T. G., U. S. Chattopadhyay, K. M. K. Sinha, K. M. P. Singh, and P. K. Singh. 2018. Beneficiation and utilization of low volatile coking coal and non-linked washery Indian coking coals for metallurgical purposes. *Journal of Mines, Metals and Fuels* 66 (7):365–69.
Chattopadhyaya, U. S., and T. G. Charan. 2021. Utilization of high ash, low volatile coking coals of jharia coalfield, india for coke making. *Coke and Chemistry* 64 (1):12–17. doi:10.3103/S1068364X21010026.
Chaudhuri, S., V. K. Kalyani, T. G. Charan, S. Kumari, and A. Sinha. 2014. Improved collector for beneficiation of low-volatile medium ash clean coal fines by froth flotation. *International Journal of Coal Preparation and Utilization* 34 (6):321–31. doi:10.1080/19392699.2014.896350.
Chaurasia, R. C., and S. Nikkam. 2017. Optimization studies on a multi-gravity separator treating ultrafine coal. *International Journal of Coal Preparation and Utilization* 37 (4):195–212. doi:10.1080/19392699.2016.1149474.
Chaurasia, R. C., D. Sahu, and S. Nikkam. 2018. Cleaning of coal by multi gravity separator. *Transactions of the Indian Institute of Metals* 71:1487–95. doi:10.1007/s12666-018-1284-1.
Das, A., and B. Sarkar. 2018. Advanced gravity concentration of fine particles: A Review. *Mineral Processing and Extractive Metallurgy Review* 39 (6):359–94. doi:10.1080/08827508.2018.1433176.
Dey, S., and S. Pani. 2012. Effective processing of low-volatile medium coking coal fines of Indian origin using different process variables of flotation. *International Journal of Coal Preparation and Utilization* 32 (6):253–64. doi:10.1080/19392699.2012.699009.
Fitzpatrick, R., P. Hegarty, K. Fergusson, G. Rollinson, W. Xie, and T. Mildren. 2018. Optimisation of a multi-gravity separator with novel modifications for the recovery of ferberite. *Minerals* 8 (191):1–18. doi:10.3390/min8050191.
Geological Survey of India (GSI). 2019. Report, inventory of indian coal resources, Government of India, New Delhi.
Goktepe, F. 2005. Treatment of lead mine waste by a Mozley multi-gravity separator (MGS). *Journal of Environmental Management* 76:277–81. doi:10.1016/j.jenvman.2005.01.026.
Hamidreza, H., J. Esmaeil, and S. Abbas. 2012. Evaluation of mayer curve validity on feed blending at the Zarand coal washery plant. *International Journal of Mining Science and Technology* 22:19–22. doi:10.1016/j.ijmst.2011.07.003.
Honaker, R. Q. 1998. High capacity fine coal cleaning using an enhanced gravity concentrator. *Minerals Engineering* 11 (12):1191–99. doi:10.1016/S0892-6875(98)00105-8.
Jyoti, D., S. Bhattacharya, A. Anupam, and V. K. Saxena. 2015. Washing of low volatile coking (LVC) coal: Is that difficult? *Transactions of the Indian Institute of Metals* 68 (4):649–60. doi:10.1007/s12666-014-0495-3.
Kopparthi, P., A. Awasthi, D. Sachinraj, and A. K. Mukherjee. 2019. Beneficiation of coal fines using the Reflux™ Classifier. *Minerals Engineering* 136:110–19. doi:10.1016/j.mineng.2019.03.018.
Luttrell, G. H., R. Q. Honaker, and D. L. Phillips. 1995. Enhanced gravity separators: New alternatives for fine coal cleaning. *Proceedings, 12th International Coal Preparation Conference*, Lexington, Kentucky, pp. 281–92.
Majumder, A. K., K. S. Bhoi, and J. P. Barnwal. 2007. Multi-gravity separator: An alternate gravity concentrator to process coal fines. *Minerals & Metallurgical Processing* 24 (3):133–38.

Menendez, M., M. Gent, J. Toraiio, and I. Diego. 2007. Optimization of multi gravity separation for recovery of ultrafine coal. *Minerals & Metallurgical Processing* 24 (4):253–63.
Mohanty, M. K., A. R. Samal, and A. Palit. 2008. Evaluation of an enhanced gravity-based fine-coal circuit for high-sulfur coal. *Minerals & Metallurgical Processing* 25 (1):13–18.
Nayak, A., M. S. Jena, and N. R. Mandre. 2021. Application of enhanced gravity separators for fine particle processing: An overview. *Journal of Sustainable Metallurgy* 7:315–39. doi:10.1007/s40831-021-00343-5.
Özbakir, O., S. Koltka, and E. Sabah. 2017. Modeling and optimization of fine coal beneficiation by hydrocyclone and multi-gravity separation to produce fine lignite clean coal. *Particulate Science and Technology* 35 (6):712–22. doi:10.1080/02726351.2016.1194351.
Özgen, S., V. O. Türksoy, E. Sabah, and F. Oruç. 2009. Process development studies on recovery of clean coal from ultrafine hard coal tailings using enhanced gravity separator. *The Canadian Journal of Chemical Engineering* 87 (5):715–25. doi:10.1002/cjce.20206.
Özgen, S., Ö. Malkoç, C. Dogancik, E. Sabah, and F. O. Sapçi. 2011. Optimization of a multi gravity separator to produce clean coal from Turkish lignite fine coal tailings. *Fuel* 90 (4):1549–55. doi:10.1016/j.fuel.2010.11.024.
Ramudzwagi, M., N. Tshiongo-Makgwe, and W. Nheta. 2020. Recent developments in beneficiation of fine and ultra-fine coal -Review paper. *Journal of Cleaner Production*. doi: 10.1016/j.jclepro.2020.122693 – in press.
Roy, S. 2009. Recovery improvement of fine iron ore particles by multi gravity separation. *The Open Mineral Processing Journal* 2:17–30. doi:10.2174/1874841400902010017.
Saikia, K., and B. C. Sarkar. 2013. Coal exploration modelling using geostatistics in Jharia coalfield, India. *International Journal of Coal Geology* 112:36–52. doi:10.1016/j.coal.2012.11.012.
Sarkar, B., S. C. Sekhar, and A. Das. 2007. Advanced gravity separators - A review of state of the art technology. *Proceedings, Advanced Gravity Separation*, *NML, Jamshedpur*, India, pp. 57–74.
Tripathy, S. K., Y. R. Murthy, V. Tathavadkar, and M. B. Denys. 2012. Efficacy of multi gravity separator for concentrating ferruginous chromite fines. *Journal of Mining and Metallurgy* 48 A (1):39–49.
Venkatraman, P., G. H. Luttrell, R. H. Yoon, F. S. Knoll, and M. J. Mankosa. 1995. Fine coal cleaning using the multi-gravity separator. In *International symposium on high efficiency coal preparation*, ed. S. K. Kawatra, 109–17. Littleton, Colorado: Society for Mining, Metallurgy, and Exploration, Inc.
Wang, G., X. Bai, C. Wu, W. Li, K. Liu, and A. Kiani. 2018. Recent advances in the beneficiation of ultrafine coal particles. *Fuel Processing Technology* 178 (39):104–25. doi:10.1016/j.fuproc.2018.04.035.