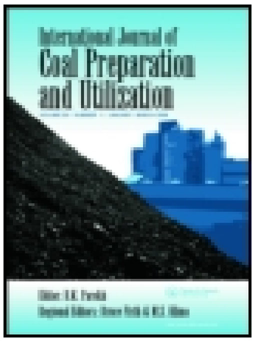

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Beneficiation of difficult-to-wash Indian low volatile coking coal fines by Falcon concentrator

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ABSTRACT

The fast depleting reserves of high-grade Indian coking coal and its resultant dependence on import makes the emerging situation a fit case for exploring innovative and high efficacy techniques such as non-conventional gravity-based systems for clean coal recovery viz., advanced centrifugal gravity separators like Falcon concentrators for fine and ultra-fine coal particles processing using enhanced gravitational force. The above methodology has been adopted for low volatile coking (LVC) coal due to the high ash content associated washability characteristics and high near gravity material content. Attempt was made using laboratory Falcon SB40 concentrator for cleaning the LVC coals assaying 32.6% ash. Considering the physical properties, coal petrography and washability studies, as received coal was ground to three size fractions of −500 µm, −250 µm and −150 µm and subjected to separation in Falcon separator. Experiments were conducted using Design Expert software to evaluate the effects of four significant process variables such as feed size, pulp density, gravitational force value and water pressure. The relationship between the response functions (ash content, combustible recovery and separation efficiency) and process variables is presented as empirical model equations. Under the optimum operating conditions, LVC coal was cleaned to 18.4% ash content with 57.8% combustible recovery using Falcon concentrator.

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LVC coal; Falcon concentrator; Box-Behnken design; beneficiation; separation efficiency

Introduction

Indian coal seams are of drift origin, comprising of varying undesirable minerals and of combustible nature. This coal being high in ash content entails extensive washing. The coking coal category reserves (35 billion tonnes) are very less in India in comparison to other non-coking coal reserves (289.9 billion tonnes) as on 1 April 2019 (GSI report, 2019). The reserves of good-grade prime coking coal of higher seams have depleted due to extensive mining exploitation and hence necessitates utilization of the remaining lower seams of poor-grade coking coals for metallurgical industry (Bhattacharya 2009: Charan et al. 2018). More than 50% of total Indian coking coal reserves correspond to low volatile coking (LVC) coals of lower seams. LVC coals are likely to be more matured (Ro ~1.3%) as compared to the higher seams variety that demonstrates lower volatility value in the lower seams (Jyoti et al. 2015). Beneficiation of these coals is challenging due to the heterogeneous

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characteristics associated with mineral matter in the coal apart from being high in ash content, near gravity material (NGM) and poor washability characteristics. It is for these inherent complexities, LVC coals are classified as non-linked washery (NLW) grade coal that finds extensive utility prospect and value in non-metallurgical applications in thermal power plants (Charan et al. 2018).

Froth flotation technique is generally adopted in coal industry for processing of coal fines and ultrafines, and the extent of fineness is dependent on the flotation methodology deployed since this has direct bearing on the recovery of combustibles from ash. The dosage of the collector has a significant effect on flotation performance (Dey and Pani 2012). An improved collector derived from coal tar was found by Chaudhuri et al in 2014 wherein concentrate with a yield of 83% and low-ash content of 16% was obtained in the flotation using the specific coal tar, while the yields with diesel oil and N-dodecane as the collectors were found to be only 71.4% and 66.7%, respectively. However, for some difficult-to-float coals such as low-rank coal and oxidized coal, the conventional flotation method is not effective because of their hydrophilic surfaces (Bhattacharya et al. 2016). Very recently, the washability characteristics of high ash and difficult-to-wash low-volatile coking coals from Jharia coal fields have revealed that a theoretical yield of 23% and 17.7% at a clean ash content of 18% with the fraction 75–0.5 mm can be utilized for coke making (Chattopadhyay and Charan, 2021). Elaborate research studies guided utilization of these coals by deploying varied beneficiation techniques to recover the clean coking coals, for subsequent blending with good-quality coking coals in order to produce the metallurgical coke. This effectively scales down wastage of scarce coking coal reserves and successfully minimizing incremental demand, which enables reduced dependence on import of coking coals.

Gravity-based processing and beneficiation techniques are adopted in coal preparation washeries due to inherent simplicity, high efficacy, low processing costs and environmentally acceptable methodology (Burt 1999). A study has been carried out using dense medium in a continuous gravity separator for the treatment of fine coal to know the technical feasibility and associated benefits (Honaker, Singh, and Govindarajan 2000). Reflux Classifier, which is a combination of the liquid fluidized bed, autogenous dense medium and lamella settle was also applied for the beneficiation of fine coal (Kopparthi et al. 2019). However, beneficiation of difficult-to-wash coal fines by conventional gravity techniques leads to reduced separation efficiency and significant loss of fine clean coals getting wasted as tailings (Can, Ozgen, and Sabah 2010: Foucaud et al. 2019; Honaker, Wang, and Ho 1996; Zhu, Tao, and Sun 2017a). Therefore, significant development has been accomplished in the gravity separation sphere to treat fine particles by applying enhanced gravitational force (Kroll-Rabotin, Bourgeois, and Climent 2012; Oruç, Özgen, and Sabah 2010; Oyku 2019). It utilizes centrifugal force to increase the relative settling velocity between particles of varying size, shape and density in separation mechanism. A comprehensive review has been published recently on the developments of advanced gravity separation techniques for processing fine particles (Das. and Sarkar 2018). Enhanced gravity concentration is far more efficacious than the traditional methodology in terms of separation efficiency and finer feed size (Nayak, Jena, and Mandre 2021). Falcon concentrator has been proven to be efficient as an enhanced gravity concentrator for fine particle separation, which has the ability to supply centrifugal force up to 300 g. The enrichment of fine coals using a Falcon concentrator, Kelsey Jig and MGS was investigated. The influence of centrifugal field on settling velocity of coal particles (Luttrell, Honaker, and Phillips 1995) was discussed as well. The developments and limitations of current ultrafine coal particle beneficiation techniques as well as the future development in recovering ultrafine coal particles have been reviewed critically (Wang et al. 2018).

Several researchers demonstrated and conducted many experimental studies aimed at in-depth understanding for performance improvement of Falcon concentrator with respect to coal fines (Kroll-Rabotin, Bourgeois, and Climent 2013; Oruç, Özgen, and Sabah 2010; Tao et al. 2006; Zhu et al. 2017b). Enhanced gravity field produced by Falcon separator can effectively separate fine coal particle greater than 0.045 mm (Zhu, Tao, and Sun 2017a). Falcon concentrator was utilized to process the finest coal size fraction of –0.15 mm with 25% solid ratio varying rotation of the drum between 20 and 80 Hz. In clean coal, the ash content was reduced to 26.56% from 41.78% (Tozsin, Acar, and Sivrikaya 2018). Modeling base study with respect to free and unrestricted settling conditions for coal fines beneficiation deploying Falcon concentrator has been discussed by Boylu (2013). In recent times, limitations in separation efficacy of Falcon semi-batch concentrator with quartz-magnetite and quartz-ferrosilicon binary system have been investigated (Singh et al. 2021). Based on the research findings, Falcon unit has been observed to be more effective and cost efficient than currently used technologies for the treatment of fine coal (Boylu 2013; Zhu et al. 2016). Studies focused upon effective cleaning the coal fines and difficult to wash LVC coals using Falcon concentrator to obtain quality product with substantive combustible recovery have not been accomplished so far, to the knowledge of the authors. Therefore, the purpose of this investigative study is for determining the feasibility of cleaning low-volatile coking coal adopting process variables for obtaining metallurgical-grade coal in a laboratory model Falcon SB40 separator. Box-Behnken Design (BBD) with Design-Expert 6.0 software has been used to design and optimize the process parameters of the Falcon concentrator.

Materials and Methods

Raw Material

A low volatile coking coal sample of below 50 mm was collected from Eastern sector of Jharia coal fields for the present study. The as-received sample was further reduced to below 1 mm size using laboratory jaw crusher followed by roll crusher for further reduction. Representative sample was collected by coning and quartering method for detailed qualitative as well as quantitative studies.

Methods

Characterization

The characterization was done in terms of size analysis, proximate analysis, ultimate analysis, petrography characteristics and sink & float tests. The proximate analysis of representative sample was obtained using coal analyzer as shown in Table 1. It indicated the ash content of the sample to be 32.6%, with low volatile matter of about 16.8%, and other constituents have been shown in Table 1. The gross calorific value of the sample was found to be 5814.62 kcal/kg, showing that the coal has good amount of heating value; however, it essentially needs be further enhanced for coke making process. The ultimate analysis of the

Table 1. Physical characterization of LVC coal sample.

Proximate analysis		Ultimate analysis		Petrographic analysis	
Constituents	wt.%	Composition	%	Macerals	Vol. %
Moisture	0.82	Carbon	61.95	Vitrinite	40.36
Volatile matter	16.80	Hydrogen	3.33	Inertinite	26.71
Ash content	32.60	Nitrogen	1.33	Liptinite	1.61
Fixed carbon	49.78	Sulfur	0.52	Mineral matter	31.32
Gross calorific value (GCV) = 5814.62 kcal/kg				Reflectance (Ro)	1.15

sample was determined by CHNS analyzer, which revealed that about 61.95% carbon was present in the coal and the average sulfur content of the sample was 0.52%. Coal petrography was done through Advanced Polarizing Microscope (Leica DM4500, Germany) on polished sample. The petrographic analysis indicates the average mineral matter content of the sample to be 31.32%. The maceral group constituents have been shown in Table 1. From the petrographical examination of the coal sample (Figure 1), the mineral matter was found to be rich with quartz and silica group minerals. Among the various macerals, the presence of vitrinite macerals is found to be dominating followed by the presence of inertinite and liptinite macerals. The reflectance (Ro) of the sample was 1.15% showing that coal is highly matured and it authenticates the lower values of volatile matter. The microphotographs that represent the distribution of macerals and mineral matters are depicted in Figure 1. It is

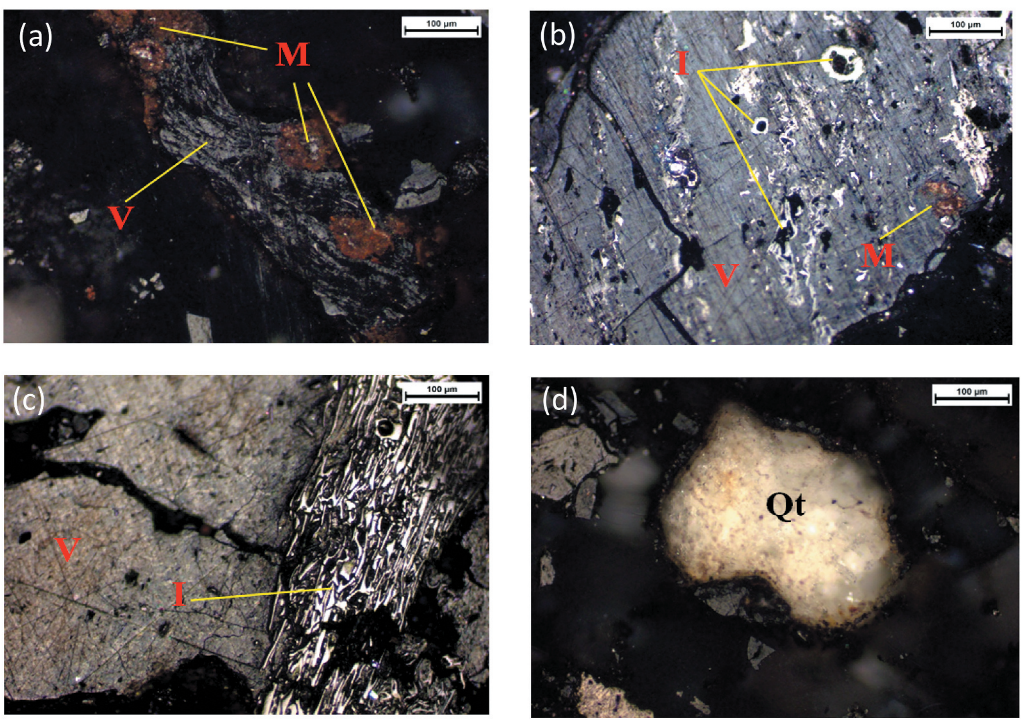

Figure 1. Microphotographs of LVC coal sample. (a) Vitrinite (V) and clay mineral matters (M). (b) Vitrinite (V), inertinite (I) and mineral matter (M). (c) Vitrinite (V) and inertinite maceral (I). (d) Typical quartz (Qt) grain.

observed from the figure that the mineral matter has inter-grown disseminated particles within the macerals group, and because of this interlocking, the washability of the coal sample is quite difficult obstructing the recovery of clean coal.

The washability characteristics of head sample ground to below 1 mm size fraction were determined by the sink & float tests in high-speed centrifuge separator (Carpco, Inc., USA, Model C-6000) using mixtures of organic heavy liquids. The relative density (RD) increment was maintained 0.1 (1.3 to 2.0), and experiments were conducted as prescribed by Indian standard procedure (IS 13810, 1993) to assess the cleaning potential of a coal sample. The sink & float test products were collected separately, dried, weighed and then analyzed for ash percentage. Figure 2 shows the fundamental washability plots such as characteristics curve, floats curve, sink curve, yield gravity curve and NGM curve using sink & float data. It can be observed from the characteristics curve of coal sample that 20–40% of total weight was found in the RD range of 1.4–1.5 fraction, which indicates the reliability of washability data. The same was maintained by the NGM curve. The slope of the float curves appears to be very steep within the RD range. A steady smooth curve was observed from sink data, indicating poor liberation at higher range of RD fractions. Maximum NGM value was observed at lower range of RD revealing the inter-growth of LVC coal with fine dissemination of mineral matter significantly. The washability data shows that theoretically 70.6% yield of clean coal was achievable at 18% ash with rejection of 29.4% by weight at 70.2% ash. The combined washability data demonstrates that LVC coal can be cleaned at finer size considering NGM values, which represents inter-lock particles, and its value was high in the lowest RD fractions.

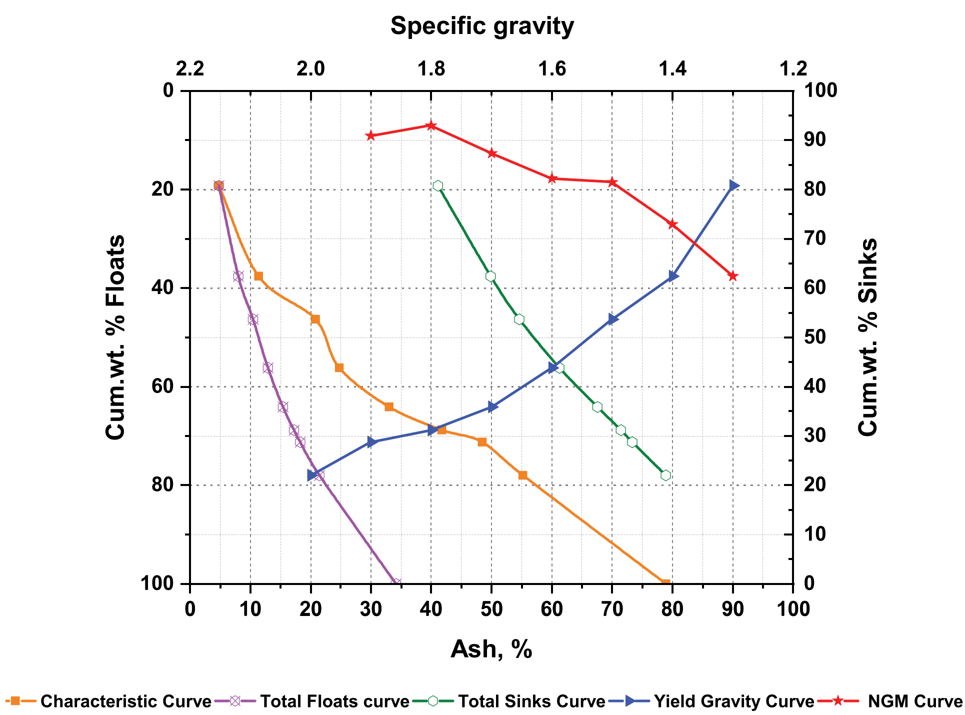

Figure 2. Washability characteristics of LVC coal sample.

Considering the characterization and washability studies of the LVC coal sample, it was found that cleaning amenability of coal sample was significantly achievable in finer size since effective liberation efficiency of the sample occurs below 1 mm size. To establish the effect of particle size, the sample was ground in a rod mill to the sizes of −500 µm, −250 µm and −150 µm separately. Each fraction of coal sample was used for the beneficiation studies using Falcon concentrator. The size distribution along with size-wise ash distribution of three feed samples was carried out and is presented in Table 2. The size analysis data indicates that ash content of each size fraction were evenly distributed, and the higher value of ash content was observed below 45 µm size, implying effective recovery of clean coal at finer size. The average ash content of the feed sample was found to be about 32.6%.

Beneficiation

Beneficiation of LVC coal was performed by centrifugal gravity separator using Semi-Batch Falcon SB40 concentrator (Figure 3). The Falcon concentrator consist of a polyurethane rotating cylindrical bowl with porous stepwise grooves (ribs) throughout the cross-section

Table 2. Size analysis and size-wise ash analysis of three different feed samples.

	Feed: −500 µm		Feed: −250 µm		Feed: −150 µm	
Size, µm	Wt, %	Ash, %	Wt, %	Ash, %	Wt, %	Ash, %
−500 + 300	29.9	29.6	-	-	-	-
−300 + 250	9.6	33.2	-	-	-	-
−250 + 150	19.6	32.8	25.0	32.7	-	-
−150 + 75	13.1	32.6	26.4	32.2	26.8	32.3
−75 + 45	5.7	32.6	12.0	31.9	19.8	33.6
−45	22.0	35.6	36.7	33.4	53.4	32.8
Total	100.0	32.5	100.0	32.7	100.0	32.8

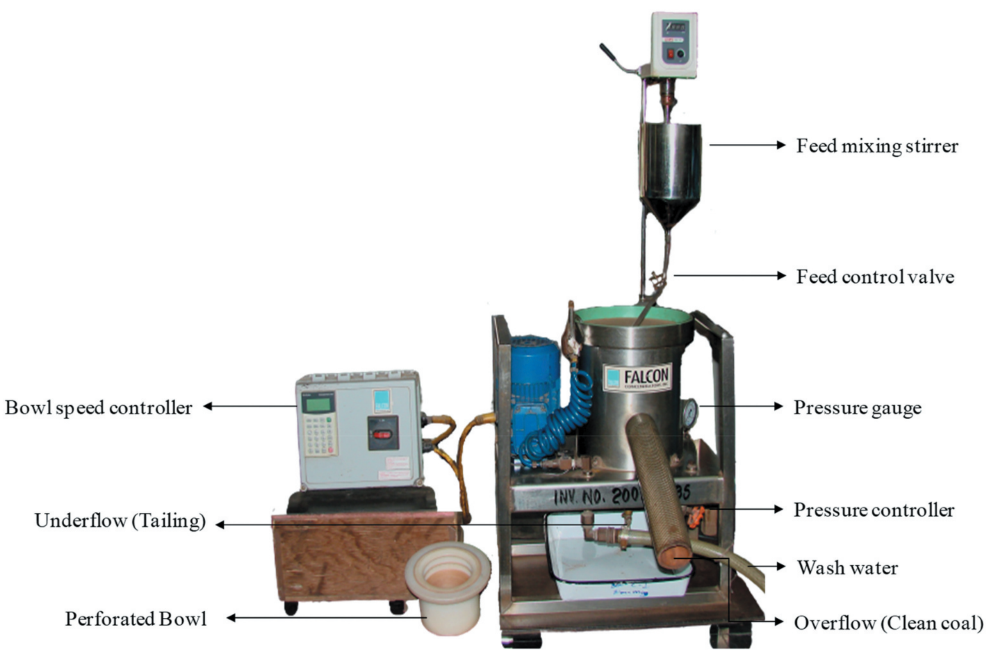

Figure 3. Schematic representation of Falcon SB40 concentrator.

of the bowl. Feed slurry coal is introduced from the top of the Falcon through stirring feeder after adjusting the bowl rotating speed and water pressure at the bottom of the unit. Quick stratification occurs as the material is flowing by centrifugal force inside the rotating bowl. Lighter clean coal particles are thrown over the top of the cone, while heavier mineral matter particles are trapped between the ribs of the bowl. Bottom injected back water pressure passes through the porous grooves, which provide cleaning of the heavy particles bed in the ribs enhancing the separation efficiency.

A series of 29 experiments were conducted using response surface methodology (Box-Behnken Design matrix) in order to assess the effects of operational parameters to obtain clean coal. Response Surface Method (RSM) is useful to determine the most influenced process variables and also quantifies the relationship among the different variables and response surfaces to acquire optimum conditions (Aslan and Cebeci 2007). The common process variables that are significantly influencing the Falcon performance are, namely bowl rotation speed (reflects G-value), solids concentration, back water pressure, feed particle size, feed flow rate, washing time, feed weight and type of material. However, potentially most effective four operational variables such as Feed size (μm), solids concentration (%), backwater pressure (psi) and G-value (g) were considered in the present study and designated as X_1, X_2, X_3 and X_4, respectively. The low, middle and high levels of each variable were designated as − 1, 0 and +1, respectively. Based on the initial few exploratory studies, the variables and levels of the Falcon experimentation was established. The levels of four variables chosen for the design of experiments are listed in Table 3. However, feed rate and washing time were kept constant at 4.5 lpm and 3 minutes, respectively, for all experiments. Feed sample was introduced at the top of the Falcon through a cylindrical feed vessel with an agitator to mix the sample properly. Due to the effect of centrifugal force generated by rotating bowl, stratification of particles occurred along the wall of the bowl. Lighter coal particles were withdrawn through the overflow pipe continuously, whereas heavier particles were collected from the bowl after completion of the experiment. Each experiment was conducted twice and the individual products were merged to minimize the experimental error. The collected products were dried, weighed and analyzed for ash content, and the same procedure was followed for all experiments. The results were analyzed statistically by inserting the data into the design expert software.

The Falcon concentrator performance was evaluated in terms of combustible recovery (%), ash rejection (%), separation efficiency (%) along with yield (%) and ash content (%) in the clean coal. The results of all the experiments were finally estimated and compared by applying following equations (Banerjee et al. 2003) for evaluating the responses.

Table 3. Experimental conditions selected for Falcon concentrator.

			Levels of variables		
No.	Process variables	Symbol	Low (−1)	Middle (0)	High (+1)
1	Feed Size (μm)	X_1	−150	−250	−500
2	Solids concentration (%)	X_2	10	20	30
3	Water pressure (psi)	X_3	1	3	5
4	G-value (g)	X_4	45	125	240

$$\text{Combustible recovery, \%} = \frac{(\%\text{Yield of cleancoal}(\text{Yc}))(\%\text{ combustible in clean coal})}{\%\text{ Combustible in the feed}} = \frac{\text{Ye}(100 - \text{Ac})}{(100 - \text{Af})} \tag{1}$$

$$\text{Ash rejection, \%} = 100 - \text{Ash recovery in clean coal} = 100\ \frac{\text{YcAc}}{\text{Af}} \tag{2}$$

$$\text{Separation efficiency, \%} = \text{combustible recovery} - \text{ash recovery} \tag{3}$$

Where Ac and Af are ash contents(%) of clean coal and feed respectively.

The detailed experimental process conditions along with calculated values of clean coal yield, ash content, combustible recovery, ash rejection and separation efficiency from the Falcon concentrator are listed in Table 4. The obtained experimental data were analyzed and accomplished with response surface regression method by Box-Behnken Design (BBD) to find out the empirical model equations. These equations provide the relationship of the response functions on input variables. Effect of process variables on responses were assessed

Table 4. Experimental runs for Box-Behnken design and its responses.

	Level of process variables				Responses				
Exp. No.	Feed size (μm)	Solids %	Water pressure (psi)	G-value (g)	Yield (%)	Ash (%)	Combustible recovery (%)	Ash rejection (%)	Separation efficiency (%)
1	−250	30	3	240	59.61	22.53	68.38	58.64	27.02
2	−500	10	3	125	53.42	24.52	59.90	59.92	19.82
3	−500	20	3	45	65.95	26.40	72.23	46.92	19.15
4	−250	30	5	125	79.81	25.93	87.01	35.44	22.45
5	−250	10	3	45	87.08	27.21	93.59	26.58	20.18
6	−250	10	5	125	75.52	25.12	83.90	41.80	25.70
7	−150	20	1	125	87.03	27.90	93.53	26.24	19.77
8	−500	20	1	125	47.15	25.40	52.02	63.01	15.02
9	−250	20	3	125	71.38	24.27	79.61	46.04	25.64
10	−250	10	3	240	61.43	21.16	71.61	59.85	31.46
11	−250	20	1	45	73.66	26.10	80.93	41.27	22.20
12	−250	20	3	125	71.96	24.21	80.52	46.00	26.53
13	−500	20	5	125	60.46	24.25	67.77	54.80	22.57
14	−150	20	3	240	85.79	27.90	92.24	27.33	19.57
15	−500	20	3	240	45.35	26.32	49.34	63.01	12.35
16	−150	10	3	125	96.01	30.80	98.45	9.05	7.50
17	−250	10	1	125	58.03	22.20	66.97	60.45	27.42
18	−150	20	5	125	95.10	31.10	97.62	10.04	7.66
19	−250	20	1	240	54.77	22.78	62.72	61.68	24.40
20	−150	30	3	125	94.72	30.00	97.83	11.83	9.67
21	−500	30	3	125	52.35	25.80	57.92	59.00	16.92
22	−250	20	5	240	70.19	24.09	78.71	47.65	26.36
23	−250	20	3	125	72.52	24.54	80.71	44.73	25.44
24	−250	30	1	125	60.50	23.17	68.71	56.66	25.37
25	−250	20	3	125	71.88	24.16	80.24	45.82	26.06
26	−250	20	5	45	89.94	28.30	95.05	20.84	15.89
27	−150	20	3	45	95.54	31.20	97.85	9.21	7.06
28	−250	30	3	45	87.49	27.30	93.82	25.83	19.65
29	−250	20	3	125	71.62	24.44	80.00	45.89	25.88

by 3D surface plots, and the experimental and predicted responses also were evaluated using Design Expert software. The model performance has been verified by the experiments carried out in triplicate at optimum conditions and discussed.

Results and Discussion

Beneficiation studies on low volatile coking coal were carried out using Falcon concentrator at different feed sizes. The results obtained from the statistical design of experiments unraveled removal of considerable amount of ash content from the LVC coal under various process conditions. In the present investigation, the performance of the Falcon concentrator was evaluated on the basis of clean coal ash content, combustible recovery and separation efficiency. It was observed from the experimental data that the lowest ash content of about 21.16% and maximum value of separation efficacy were achieved with feed size of −250 µm, 10% of solid concentration, 3 psi of backwater pressure and 240 g of gravity value, whereas maximum percentage of combustible recovery of clean coal was noticed under the process conditions of −150 µm feed size, 20% of solids, 3 psi water pressure and G-value of 45 g. Further the effect of independent process variables on the responses was assessed with the help of model equations.

The model regression equations were derived from the analysis of variance (ANOVA) for the response functions representing coal ash (Y_1), combustible recovery (Y_2) and separation efficiency (Y_3) of Falcon concentrator and correlated with process variables feed size (X_1), solids concentration (X_2), water pressure (X_3) and G-value (X_4). The model equations for the responses developed with independent process variables, and their interaction have been mentioned in Equations 4, 5 and 6, respectively.

$$Y_1 = 26.83 - 2.92X_1 + 1.09X_3 - 0.86X_4 - 1.09X_1X_3 + 0.18X_1X_4 + 3.06{X_1}^2 + 0.05{X_4}^2 \tag{4}$$

$$Y_2 = 88.69 - 14.84X_1 + 7.09X_3 - 2.99X_4 + 2.91X_1X_3 - 0.83X_1X_4 - 1.60{X_3}^2 + 0.12{X_4}^2 \tag{5}$$

$$Y_3 = 21.06 + 7.04X_1 - 2.81X_3 + 1.45X_4 + 4.91X_1X_3 - 1.03X_1X_4 + 0.42X_3X_4 - 10.02{X_1}^2 - 0.09{X_4}^2 \tag{6}$$

The results of ANOVA (analysis of variance) obtained from the design expert software for three responses are presented in Table 5. The probability values (P value) for the three developed models were adequate (<0.05), which indicates that the derived quadratic models were significant. The standard deviations of three models are 1.0, 2.75 and 2.21 for coal ash, combustible recovery and separation efficiency, respectively. It summarizes that the experimental results are reasonably in close agreement with the predicted values. The higher value of R^2 of 0.9731 for the combustible recovery indicates that significant correlation is achieved between the experimental and predicted values. R^2 values of clean coal ash content (0.9316) and separation efficiency (0.9213) show experimental values are reasonably in close agreement with predicted values as per the model. In addition, the lack of fit F-values of 47.35, 49.41 and 34.42 implies that the lack of fit is significant for all the three quadratic models,

Table 5. Analysis of variance (ANOVA) for three responses.

Statistics	Ash	Combustible recovery	Separation efficiency
Model	Quadratic	Quadratic	Quadratic
Mean square	27.43	817.83	142.29
F-value	27.68	108.41	29.25
P-value	<0.0001	<0.0001	<0.0001
R^2-value	0.9316	0.9731	0.9213
Lack of Fit	47.35	49.41	34.42
Standard deviation	1.0	2.75	2.21

Table 6. Model term wise *P* values of three responses.

	P values of responses		
Model terms	Ash	Combustible recovery	Separation efficiency
X_1	<0.0001	<0.0001	0.0003
X_3	0.0163	<0.0001	0.0155
X_4	0.0031	0.0555	0.0079
X_1X_3	0.0485	0.0364	0.0049
X_1X_4	0.0553	<0.0001	0.0029
X_3X_4	-	-	0.0408
X_1^2	<0.0001	-	<0.0001
X_4^2	0.0553	0.0126	0.0535

respectively. In regression analysis, coefficient of *P* values determines the mathematical relationship between the variables and responses and their significance. The *P* value of each term (variables and their functions) in the model equation are shown in Table 6. 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 experimental and predicted values of the ash (%), combustible recovery (%) and separation efficiency (%) obtained from the model equations have been compared and are graphically represented in Figure 4. The obtained model satisfactoriness was established from the plot between the randomized residuals and the run number, which are shown in Figure 5. It is apparent that the derived models were adequate within the levels of process conditions. The effect of process variables for achieving clean coal with desired responses have been explained using three-dimensional response surface plots.

Effect of Variables on Clean Coal Ash

Enhanced gravitational force development in the gravity-based separation technique improves the separation performance while handling fine particles. The beneficiation of low-volatile coking coal sample through Falcon separator with different gravitational force values, namely 45 G, 125 G and 240 G, were used to observe their effect on clean coal separation performance. The combined effect of G value and feed size on ash content of clean coal at the mid-levels of water pressure and solids concentration is shown in Figure 6 (a). It is observed from the 3D surface plot that minimum amount of clean coal ash content is found at high G values, which implies increasing gravitational force has greater impact on the grade of the coal. Increasing the G value increases the particle velocity toward underflow launder as a result of increased centrifugal force and reporting lighter coal particles into overflow launder with low ash content product. Figure 6(b) explains the effect of feed size and back water pressure on ash content of overflow product. It shows that the ash reduction

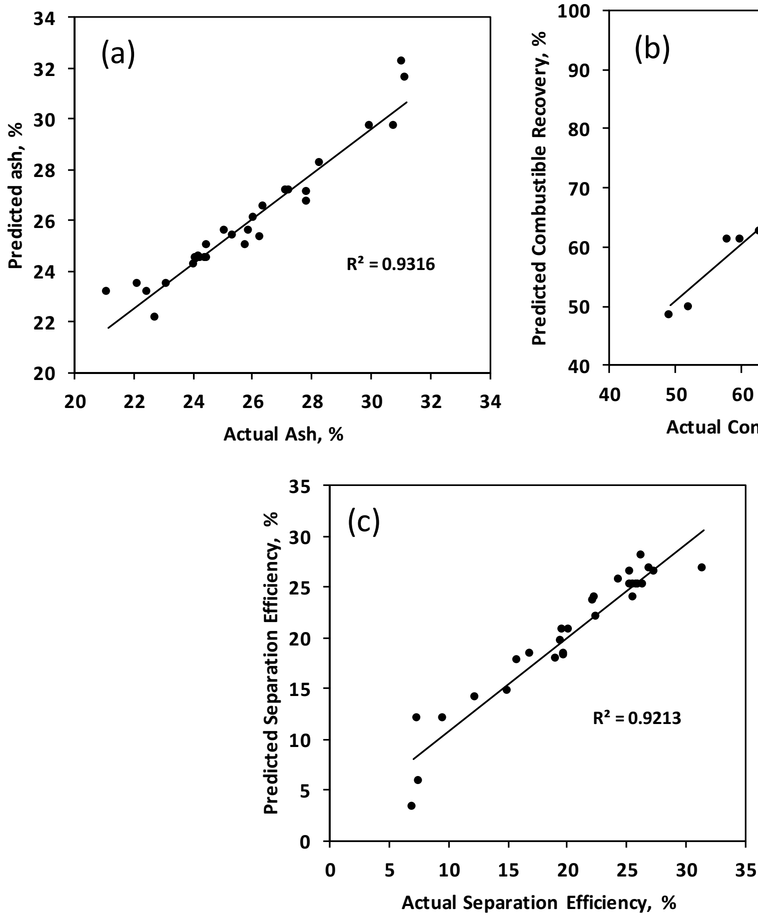

Figure 4. Correlation of actual and predicted values of (a) ash, (b) combustible recovery a (c) eparation efficiency.

was not achieved at higher fluidization water pressures and coarser feed size. This is attributable to poorly liberated high specific gravity mineral matter in the feed while operating the Falcon with higher water pressure flow toward overflow pipe, leading to high ash product in the overflow. In this study, clean coal ash reduction enhanced effectively by increasing the bowl rotational speed since the centrifugal effect of quartz rich mineral matter at high bowl speed was substantially greater than that of coal particles. Hence, the feed particles attain considerable differences between the specific gravities of mineral matter and coal particles and thereby enhances the product ash reduction by increasing the bowl speed. In other words, a reverse trend that significant deterioration of ash rejection was observed by increasing the fluidized water flow since settled bed in the bowl can be loose at high fluidized water pressure, which leads to entrapment of mineral particles into clean coal product. It is concluded that for improving the product ash level, bowl speed has to be increased to maximum range and the back water pressure must be lower, otherwise the Falcon separator will perform like a classifier.

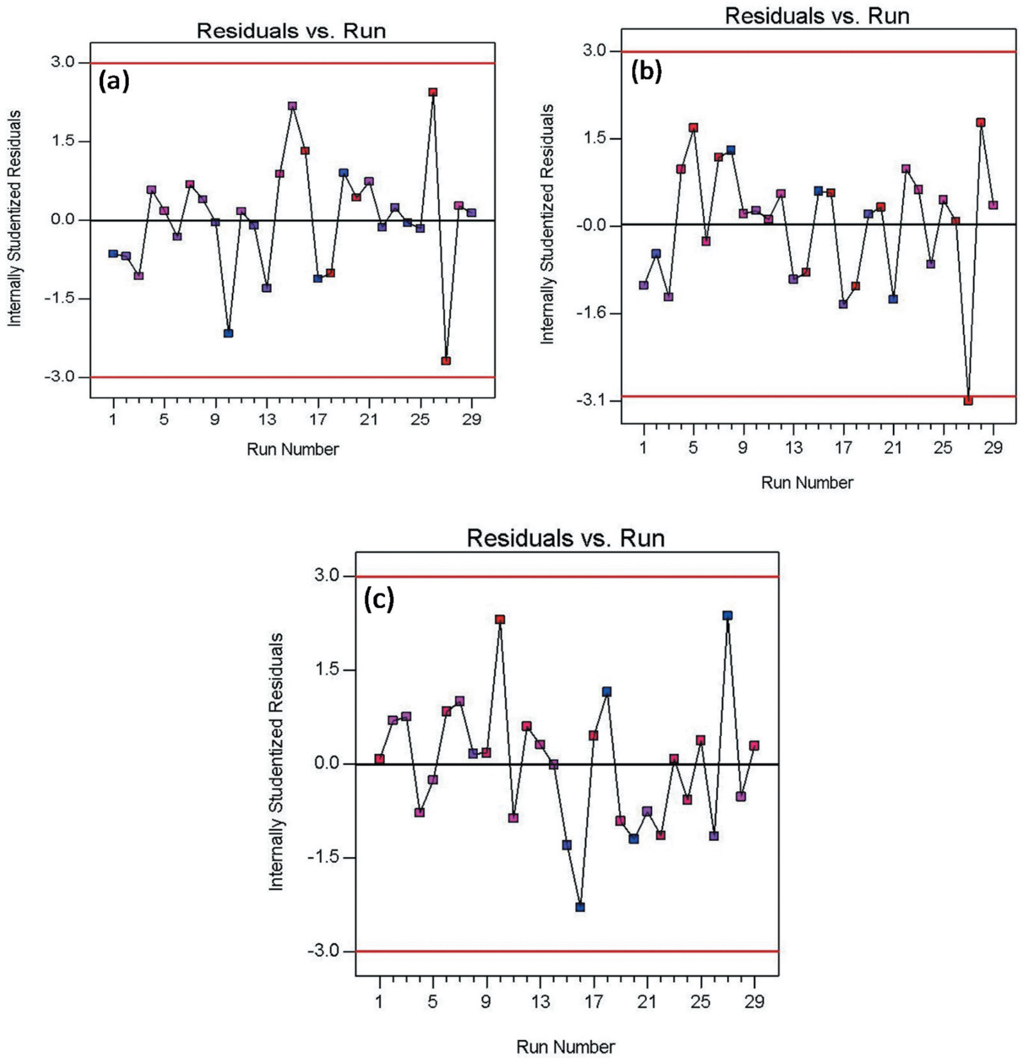

Figure 5. Residuals vs Run number for (a) ash, (b) combustible recovery and (c) separation efficiency.

Effect of Variables on Combustible Recovery

The major advantage for adopting Falcon centrifugal separator for LVC coal fine came to surface on basis of combustible recovery results at different feed sizes of −500 µm, −200 µm and −150 µm. Figure 7(a) represents the collective effect of feed size and gravitational force (G value) on combustible recovery of concentrated clean coal at the mid-levels of solid concentration and fluidized water pressure. The surface plot suggests that the maximum combustible recovery is achievable at the lowest levels of feed size and G value. It is also noticed that feed size has more significant effect on combustible recovery of clean coal. The coarse particles of feed did not respond well in Falcon due to insufficient liberation, and the finer particles feed rejected the high ash content tailing through underflow. Increasing back water pressure along with increased feed size has greater effect on combustible recovery, as is shown in Figure 7(b). It clearly reveals that

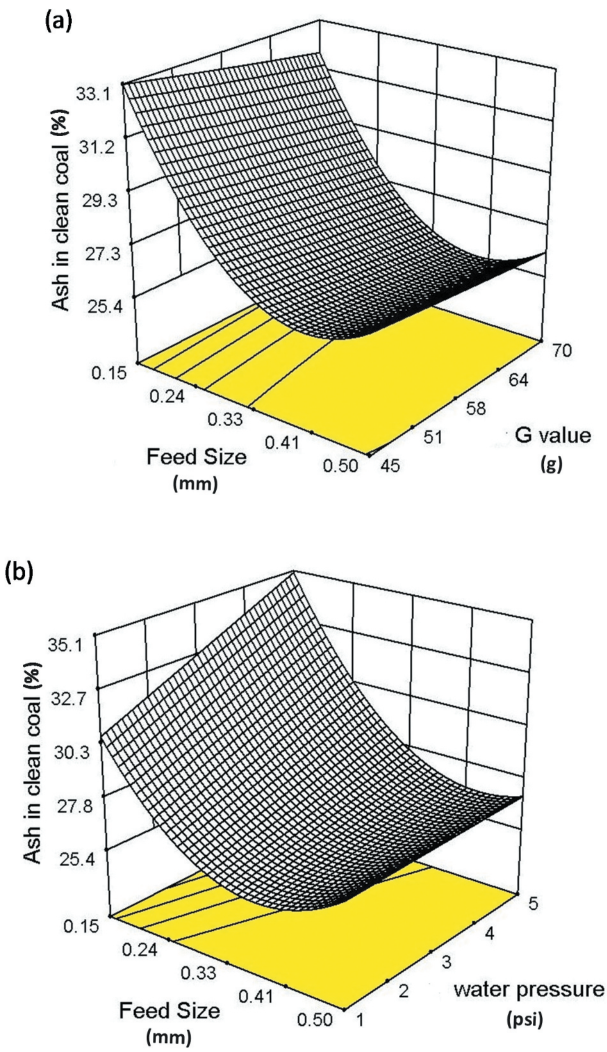

Figure 6. Effect of process variables. (a) Feed size and G-value. (b) Feed size and water pressure on clean coal ash (%).

increased fluidized water pressure affects significantly on maximum recovery of clean coal at finer feed size. It is to be recalled that the centrifugal separators like Falcon concentrator are highly efficient and suited for separation of fine particles. In addition, process conditions of low water pressure at middle level of G value have substantially decreased the yield of clean coal from the Falcon concentrator. However, in spite of cleaning difficulty of low volatile coking coal, the resultant combustible recovery values obtained by the Falcon concentrator were almost similar to washability data, considering the entire range of overflow clean coal yield and ash content.

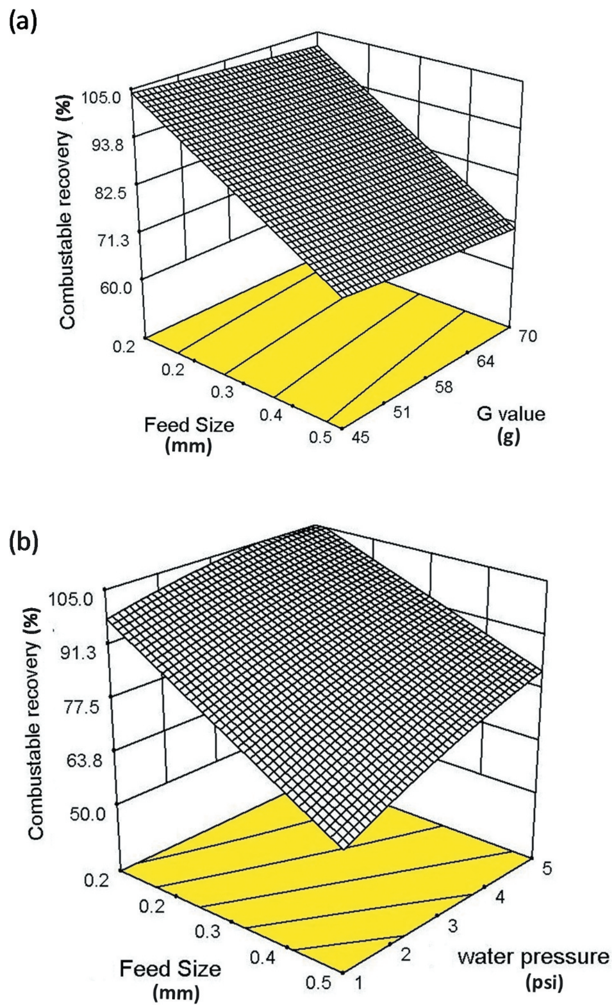

Figure 7. Effect of process variables. (a) Feed size and G-value. (b) Feed size and water pressure on combustible recovery (%).

Effect of Variables on Separation Efficiency

A series of experiments were conducted in the present study at different levels of process parameters to assess the separation efficiency of the Falcon concentrator. The results indicate that separation efficiency of Falcon was significantly affected at different solid concentrations namely 10%, 20% and 30% of LVC coal sample with various levels of other parameters. The solid concentration impacted partially the improvement of clean coal concentration; however, better results were obtained at low solid concentration. Figure 8(a) showed the effect of G value and feed size on separation efficiency performance of Falcon at the mid-levels of solids concentration and back water pressure. It has been noticed from the figure that encouraging efficiency results were achieved at higher value of gravitational force and at lower level of feed size. Maximum separation efficiency of clean coal in concentrate was obtained up to 31.46%

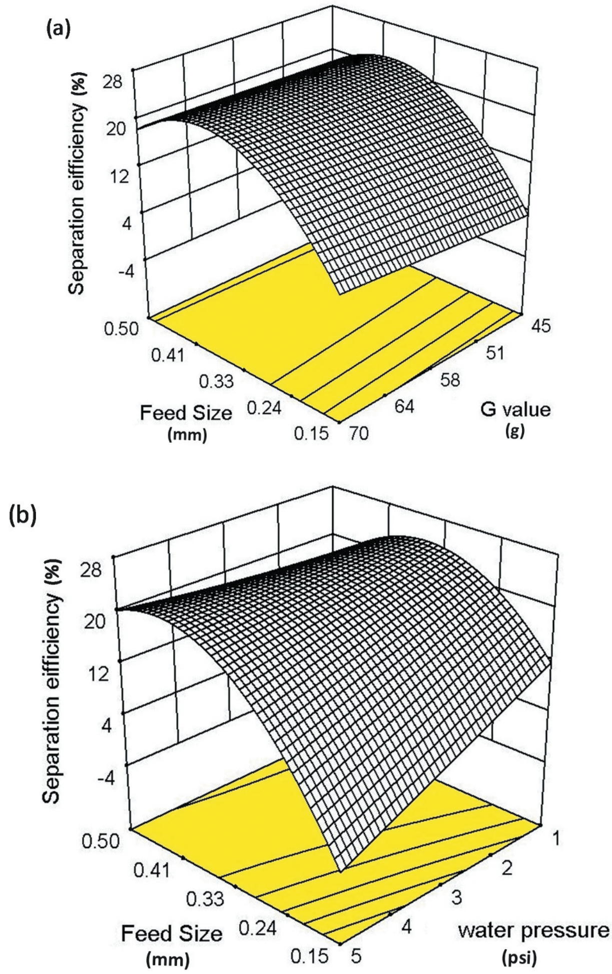

Figure 8. Effect of process variables. (a) Feed size and G-value. (b) Feed size and water pressure on separation efficiency (%).

for the feed size of −250 μm and gravity value of 240. As discussed in the earlier section, it yet again evidences that the separation performance of Falcon separator is highly efficient for the treatment of fine particle of coal sample. Increased fluidized water pressure with decreased feed particle size collectively enabled the improvement of separation efficiency of Falcon concentrator as shown in Figure 8(b). It is due to sufficient fluidized water flow to washout the lighter clean coal fine particles towards overflow that the ash percent of the concentrate could be reduced considerably and hence improves the efficiency of the concentrator. Lowering of the back water pressure at coarser feed material adversely impacts the separation performance of the Falcon. It is revealed that appropriate levels of process parameters can enhance the separation performance of Falcon concentrator for beneficiation of LVC coal.

Table 7. Two stage Falcon separation performance.

Two stage	Products		Wt., %	Ash, %	Combustible Recovery, %	Ash Recovery, %
Stage: 2	Rougher concentrate	Cleaner concentrate	47.9	18.4	57.8	27.1
		Cleaner tailing	13.5	30.8	13.9	12.8
Stage: 1	Rougher tailing		38.6	50.7	28.3	60.1
Feed			100.0	32.6	100.0	100.0

Optimum Operating Regime

The obtained empirical model equations were further optimized using Design Expert software in terms of optimum process parameters to achieve the desired grade of clean coal ash content with maximum combustible recovery and separation efficiency within the specified range of conducted experiments by Falcon concentrator for LVC coals. The desirability value of 0.97, 1.0 and 0.98 were obtained for clean coal ash, combustible recovery and separation efficiency, respectively. It unravels that the precision of developed models for optimizations is significant and adequate within the levels of process variables under investigation. The minimum ash content of clean coal of 21.2% with a yield of 61.3% and combustible recovery of 72.0% can be achieved from the feed LVC coal of 32.6% ash by optimizing the process variables at −270 μm feed size, 16% of solid concentration, 1 psi fluidized water pressure and 240 G of gravitational force. However, maximum combustible recovery of 97.2% with product ash of 26.7% can be attained in clean coal of overflow product under the optimized conditions such as feed size of −180 μm, solid concentration of 22%, water pressure of 2 psi and G value of 49 g. Similarly, maximum separation efficiency of 24.9% can be achieved using the optimum process variables at −330 μm feed size, 24% of solid concentration, 1 psi of water pressure and 240 G of gravitational force. The optimized conditions of Falcon process variables for obtaining low ash product were verified by the experiments carried out in triplicate using LVC coal samples. The results indicated that the feed of 32.6% ash content of LVC coal was reasonably equivalent and fit to model equations.

Two-Stage Cleaning

Beneficiation of LVC coal using Falcon concentrate was achieved to 21.2% ash in clean coal with 61.4% of yield from the feed ash content of 32.6% under the optimized conditions of process parameters. However, metallurgical coke feed grade of about 18% ash level has not been achieved in single-stage process. Hence, two-stage cleaning of LVC coal is imperative to achieve the objective level of ash in the final clean coal product. The clean coal concentrate obtained from the first stage was reprocessed under the same optimum conditions. Overall, the results of two-stage separation using Falcon concentrator indicated that the final clean coal ash of 18.4% was achieved with 57.8% combustible recovery, and other associated details are shown in Table 7. It is observed that two-stage Falcon concentration can achieve the desired ash content of clean coal from the LVC coal.

Conclusion

The present investigation highlights the cleaning possibility of low-volatile coking coal from Jharia coalfield having 32.6% ash content using Falcon concentrator. The washability data indicates that theoretically clean coal can be achieved at 18% ash with 70.6% yield. Among the process variables studied, it has been evidenced that higher values of G-force coupled with lower values of back water pressure has major influence on cleaning performance of Falcon concentrator using LVC coal. At the same time, the effect of solids concentration was notably insignificant on the separation efficiency. The results also indicate that variation of feed size has greater influence on the combustible recovery of the clean coal. It was observed from the Box-Behnken Design of experiments that low ash content of 21.2% with a yield of 61.4% and combustible recovery of 71.6% clean coal is achievable under optimum process conditions. The concentrate obtained was reprocessed in Falcon concentrator in order to attain the desired clean coal ash. The final product was obtained from two-stage cleaning by Falcon concentrator with 18.4% ash at 57.8% combustible recovery, which can be utilized for making metallurgical coke.

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Disclosure Statement

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

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