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Original Research Paper

Statistical optimization study of jigging process on beneficiation of fine size high ash Indian non-coking coal

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Non-coking coal is used for metallurgical and cement industries apart from generating energy. Indian non-coking coals are high in ash content because of drift origin. These high ash coals require beneficiation before being used. Jigging is one of the unit operations used for beneficiation of coal. Beneficiation by jigging is carried out for the coarser size of particles. Jigging of fine size coal is limited. However, in present study two fine non-coking coal samples having sizes −3+2 mm and −2+1 mm were used for jigging study. In present study jigging experiments were performed using laboratory Denver mineral jig by varying feed size, water rate, and feed rate. 2^3 full factorial experimental design was used to study the performance of jigging operation. The performance of jigging was judged by statistical analysis; where ash content and combustible recovery of concentrate were considered to be responses. In addition to statistical analysis, optimization study was also carried out by Nelder–Mead multidimensional pattern search method. Statistical models developed in the present study could predict ash content and yield of the concentrate accurately. At optimized condition, it was possible to achieve 22.6% ash content with 64.15% combustible recovery.

1. Introduction

Non-coking coal is one of the major sources of energy in the world today. Apart from generating energy, it is also used for metallurgical and cement industries [1–4]. India has a good reserve of non-coking coal; which are of mostly high ash content with difficult washability characteristics. Mineral matters in Indian non-coking coal is well distributed in the matrix; making it difficult for washing. The limited good quality non-coking coal reserves are depleting day by day with the increase in demand. Because of which it is now becoming necessary to beneficiate these high ash non-coking coals, for utilization in the field of power generation, steel production, and cement industries. Beneficiation is the process of separating the wanted particles (pure coal particles in this case) from unwanted particles (impure coal particles or gangue particles in this case) by exploiting the difference in their properties like physical, chemical, surface, etc.

Many experimental works were carried out in past for beneficiation or washing of coal using different methods like gravity concentrations, enhanced gravity concentrations, fluidization and floatation [5–17]. In addition to these, many mathematical modeling works were also carried out in past for quantitative representation [5,18–23]. Normally for beneficiation or washing of coarser size fractions of +3 mm coal; jigging, heavy media bath, heavy media cyclone, and air dense medium fluidized bed separators are used. However, very few literatures are available for beneficiation of coal particles within the size range of 0.5–6 mm using the vibrated air dense medium fluidized bed separator or jig [5,24]. As per the usual practice at industries −3 mm fraction of coal, generated during crushing are most of the time sent to peat head power plant as such without beneficiation [5]. These coals contain high ash, because of which the productivity of power plant decreases. Use of these fine fractions of coal after beneficiation or washing is very limited. Normally for beneficiation of −1000 +100 μm fine coal, spiral and fluidized bed separator like floatex could be used. For beneficiations coal with size fractions below 500 μm, floatation technology, and tribo-electrostatic separation could be applied [25–27].

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Jigging is a commercially successful unit operation for beneficiations of coal at coarser size range. Jigging is gravity separation process where particles are separated based on the difference in size, shape, and density. Fig. 1 shows the schematic diagram of the jig. As shown in Fig. 1 jig has the bed of particles which rests on the perforated plate or screen, hutch containing water and plunger with motor for providing pulsation. The plunger pulsates the water in hutch and water pulsates the bed of particles. During the pulsation cycle bed particles expand and settle alternatively. Because of this expansion and settling of particles, the heavier and larger particles report to the bottom of the bed and lighter and smaller particles report to the top of the bed, which results in segregation of particles. Quartz is used as the ragging material. Ragging materials are required to prevent the fine and light particles from entering the hutch for better separation. These fine and light particles come out as overflow. The fine heavier particles pass through these ragging materials and report to the hutch. Lots of literature is available for beneficiation of coal using jig including modeling and simulation studies to quantify the process [28–33]. However, use of jigging process for the beneficiation of non-coking coal at finer size range is limited [5]. Moreover statistical analysis of the jigging process is also limited [33]. Ahmed [33] studied the jigging process using statistical methods. He had taken the synthetic mixture of pure coal having the specific gravity of 1.3 and pure quartz having the specific gravity of 2.65. He studied the effect of particle size, bed thickness, water level, and frequency of jigging process. So there is a need to study jigging process using natural occurring coal with high ash content. Use of statistical analysis reduces the number of experimental runs required for studying the effect of parameters on jigging performance. The objective of the present study is to understand the impact of parameters and their interactions on the performance of jigging for beneficiation of natural occurring fine Indian high ash non-coking coal. Analysis of variance (ANOVA) was used for this purpose. Three parameters i.e., coal particle size, feed rate and water rate were considered for the study. In addition to statistical analysis, optimization of the jigging process for beneficiation of fine Indian high ash non-coking coal was also carried out.

2. Materials and methods

2.1. Jigging studies

High ash non-coking coal used for the present study was collected from Andhra Pradesh area of India. The size of the collected coal sample was −100 mm. These coals were crushed using laboratory jaw crusher to below 40 mm size. During the process of crushing −3 mm finer size fractions of coal were generated. These finer size fractions were further classified into −3+2 mm and −2+1 mm using screens. These close size fractions of coal reduce the size effect during jigging to a negligible limit. The feed rate and water rate were varied within the particular range based on the capacity and performance of the jig.

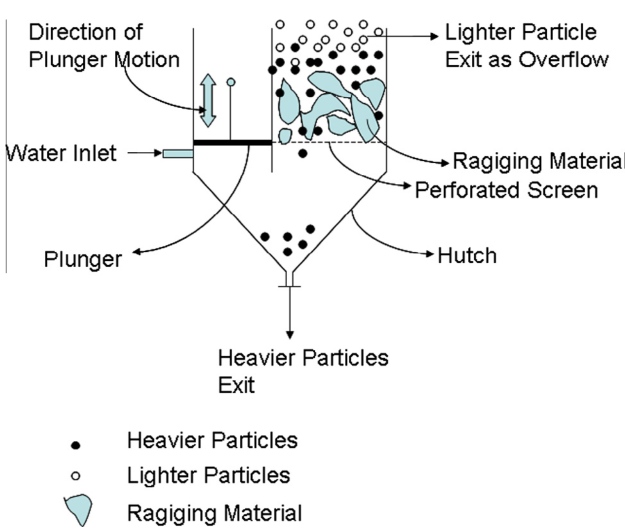

Fig. 1. Schematic diagram of jig.

Jigging experiments were performed using laboratory Denver mineral jig. Pulsation of the jig was achieved mechanically by plunger–diaphragm system. The mineral jig contains a rotating water valve which is synchronized with the diaphragm. Water enters into the jig only during the diaphragm up-stroke. During all experimental runs, the stroke length was maintained at 9/16 in. One kg of the representative sample was taken for the experiment in each run and fed at different specified time to achieve the required feed rate. Quartz particles of −15+10 mm size were used as the bed materials for all the experimental runs. After each experiment was over the concentrate (light particles) and tailings (heavier particles) were collected, dried, weighed and analyzed for ash content and combustible recovery.

2.2. Statistical analysis

Statistical analysis was carried out to find out the effect of parameters and their interactions on ash percent and combustible recovery of the clean coal obtained from the jigging. Design Expert software was used for the present study. Three variables were considered in this work i.e. coal size (A), feed rate (B) and water rate (C). A 2^3 full factorial matrix of experiments were designed for the present work, where three factors mentioned above are varied over two levels. Values of each variable are coded as −1 for low level and +1 for high level. Coal size was varied at 1.5 mm (low level) and 2.5 mm (high level). Feed rate was varied at 0.1 kg/min (low level) and 0.2 kg/min (high level). Water rate was varied to 1 l/min (low level) and 3.5 l/min (high level). Two responses were considered for this work. Combustible recovery of clean coal was considered to be one of the responses, and ash percent of clean coal was considered to be another response. Details of 2^3 full factorial experimental design matrix and the respective responses are given in Table 1 where values of the variables are given in coded form.

Optimization of the jigging process for beneficiation of Indian high ash non-coking coal was carried out in addition to statistical analysis. Optimization study in Design Expert software was performed by Nelder–Mead multidimensional pattern search method [34,35]. The Nelder–Mead method uses penalty function approach where an iterative procedure was adopted to minimize the penalty function i.e.

$$\text{Minimize} \quad \left\{ F(x) + P\sum_{j} G_j(x) \right\}$$

Table 1
Matrix of the experimental design.

Experiment run number	Coded variables			Response 1: Ash content of concentrate (%)	Response 2: Combustible recovery of concentrate (%)
	A	*B*	*C*		
01	1	1	1	34.70	96.67
02	1	1	−1	32.77	94.22
03	1	−1	1	31.71	91.85
04	1	−1	−1	28.25	88.29
05	−1	1	1	17.80	51.62
06	−1	1	−1	14.91	19.17
07	−1	−1	1	16.89	41.80
08	−1	−1	−1	13.67	5.38