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ORIGINAL PAPER

A combined approach study of dry and froth flotation techniques for optimization of resources by using CFD for quality enhancement of high ash coking coal

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Abstract

A batch-scale dry coal beneficiation process was employed for its efficiency in minimizing water usage and enhancing liberation, utilizing a gas-solid fluidized bed separator to beneficiate high-ash Indian coking coal. The present work aims to design and optimization of a batch-scale gas-solid fluidized bed separator, employing Computational Fluid Dynamics (CFD) for a parametric study, and subsequent processing with a froth flotation method. The coal was collected from Bastacolla open cast mines in the Dhanbad, Jharkhand and processed as received after crushing to -50 + 6 mm and −25 + 6 mm size fractions for dry operations in a Dense Medium Fluidized Bed separator. The −6 mm size fraction, along with pre-concentrate from the dry process, was crushed to 0.5 mm for froth flotation using various reagents such as kerosene and synthetic reagents as collectors, and Methyl Isobutyl Carbinol (MIBC) and synthetic reagents as frothers. The effects of different process parameters (bed height, dense medium size, air flow rate) of the dry separator and reagent dosage for froth flotation were evaluated. The dry process with the −25 + 6 mm fraction showed superior performance, achieving a higher yield and better ash rejection at a cut density of 1.78 compared to the −50 + 6 mm size due to enhanced washability upon liberation. Dry deshaling of high ash coking coal (-25 + 6 mm) reduced ash levels from 49% to 40% with a yield of 62.40%. The flotation process using synthetic reagents proved more effective than kerosene plus MIBC, reducing feed ash from 38.17% to 32.94% with an appreciable yield of 65.70%.

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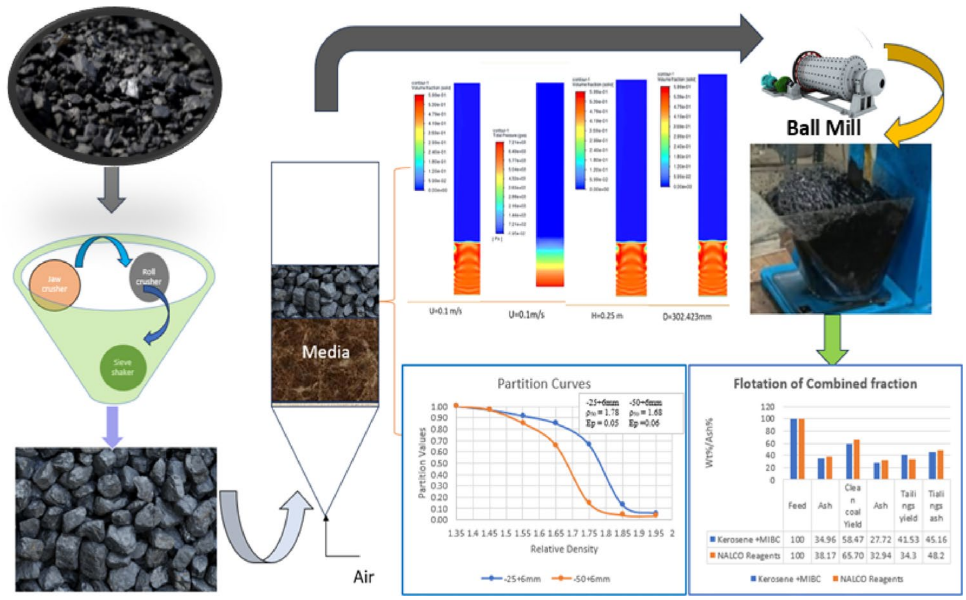
Graphical abstract



Keywords Gas–solid fluidized bed · Dry beneficiation · Froth flotation · Washability study · Dense media · Flotation reagents

Introduction

India's vast coal reserve, totalling 361.411 billion tonnes as of April 1, 2022, primarily consists of Gondwana coal (99.5%), with a small fraction of Tertiary coal (0.5%). Gondwana coal, predominantly found in regions such as the Damodar Valley (West Bengal, Jharkhand), Son-Mahanadi Valley, Godavari Valley, and Wardha Valley, is over 200 million years old and includes both coking and non-coking types. Tertiary coal deposits, around 55 million years old, are located in Meghalaya, Assam, and Arunachal Pradesh. Among these reserves, approximately 90% is non-coking coal and 10% is coking coal, both characterized by high ash content due to their drift origin (Coal Controller's Organisation 2023).

The primary challenge in processing Indian coal lies in its high mineral content, which makes it difficult to wash due to the intermixing of coal and impurities (macerals and mineral matter). This increases the near-gravity material (NGM), reducing the separation efficiency at lower cut densities. Mechanized mining further dilutes seams and deteriorates coal quality. Burning high ash coal results in increased greenhouse gas emissions, higher maintenance and operating costs, erosion, difficulty in pulverizing, and generation of fly ash. These challenges necessitate coal beneficiation to enhance coal utilization efficiency.

Coal beneficiation, as part of the "clean coal technology campaign," is crucial for producing higher quality coal for various industrial applications, including sponge iron, cement, thermal power plants, and steel plants. can Beneficiated coal significantly reduces environmental pollution by lowering COx and SOx emissions (Zhao et al. 2011) decreases erosion rates and maintenance costs by 50–60% and 35%, respectively (Couch 2002; International Energy Agency 2002; Foster et al., 2007) and increase thermal efficiencies by up to 4–5% on existing PC boilers, reducing CO_2 emissions by up to 15% (Zamuda and Sharpe 2007). While wet-type physical coal beneficiation is commonly used to reduce the ash level of coking coal to 17% for metallurgical applications, it faces several drawbacks.

Wet processing involves chemical breakdown, physical degradation of friable coal, handling problems, water loss, environmental issues, and high energy consumption (Van Houwelingen 2004). Additionally, it adds moisture to the washed coal, decreasing its thermal value and requiring additional dewatering steps, which increase costs. The environmental impact and high costs associated with the wet process restrict its application mainly to coking coal, with only 20% of non-coking coals being washed in India (Coal Controller's Organisation 2023).

In response to these challenges, dry processing methods are gaining acceptance, especially in water-scarce regions. Techniques such as the air-dense-medium fluidized bed separator, FGX dry separator, air jig, and X-ray ore sorter are effective for coarse coal processing. The air-dense-medium fluidized bed (ADMFB) separator stands out due to its higher separation efficiency and lower operating costs (Hughes et al. 2024). In an ADMFB setup, a solid medium is fluidized by upward airflow, creating a pseudo-fluid bed that separates coal based on density. Clean coal floats while denser components settle and are removed as tailings (Phengsaart et al. 2023).

ADMFB separators use magnetite particles as the medium, benefiting from their magnetic properties for easy recycling and minimal medium particle loss. These separators operate at lower air flow rates, require smaller dust-collecting equipment, and have minimal moving parts. They also allow for the use of waste heat for concurrent coal drying. Key factors influencing ADMFB performance include feed characteristics, bed stability, and operational conditions (Fu et al. 2019).

The separation performance of ADMFB is influenced by several key parameters. A greater density contrast between coal and gangue materials enhances separation efficiency (Fu et al. 2020). Larger particles, particularly those with spherical shapes, separate more effectively (Wang et al. 2014). Adjusting operational parameters such as feed rate and air velocity can also improve efficiency, with reduced feed rates and lower air velocities being beneficial (Azimi et al. 2013). The beneficiation of small South African coal can be effectively achieved using an air dense medium fluidized bed, which has been assessed for its ability to efficiently handle small coal particles. Additionally, maintaining a lower bed height and a higher magnetite content within the bed can further enhance separation (Diedericks et al. 2022). The size of the bubbles within the fluidized bed also plays a role, with smaller bubbles helping to lower the ash content in the final product (Zhang et al. 2017). Lastly, longer processing times generally lead to increased segregation efficiency (Jiang et al. 2019).

Utilizing Computational Fluid Dynamics (CFD) can significantly enhance coal beneficiation processes in gas-solid fluidized beds, optimizing separation efficiency and improving process parameters (Zhang et al. 2020a, b). The beneficiation of coarse coal ore can be effectively achieved using an air-fluidized bed dry dense-medium separator, with a focus on optimizing its design and performance for improved efficiency (Firdaus et al. 2012). The size and shape of feed-coal particles play a crucial role in determining the separation efficiency in gas-solid fluidized beds, with both particle size and lump coal shape significantly impacting the performance of dry coal beneficiation processes (Zhao et al. 2015; Zhao and Wang 2010). The performance of a Dense Medium Gas-Solid Fluidized Bed Separator (DMFBS) for coal cleaning and upgrading has been investigated, demonstrating its effectiveness in density-based segregation of high-ash coal. This technology shows potential for enhancing coal quality by reducing ash content and improving separation efficiency (He et al. 2016a). The study presents a numerical study using a Two Fluid Model – Discrete Element Method (TFM-DEM) hybrid model to investigate particle segregation in a coal beneficiation fluidized bed. It examines how variations in coal particle size and density influence segregation performance. The study provides insights into optimizing fluidized bed operations for effective coal separation, highlighting the impact of particle characteristics on the efficiency of the beneficiation process (Wang et al. 2015a). The study explores particle motion and separation behavior in a gas–solid separation fluidized bed. It investigates how coal particles interact within the fluidized bed environment, focusing on factors influencing their motion and the effectiveness of the separation process. The findings offer valuable insights into optimizing fluidized bed operations for improved coal separation efficiency (Lv et al. 2018). The study examines the rejection of ash and mercury from fine coal using an air dense fluidized bed with a shallow bed height. It assesses the effectiveness of this setup in removing undesirable components from coal, providing insights into optimizing bed height for enhanced deash and mercury removal efficiency (Zhang et al. 2020a, b). The study introduces a method to enhance fluidization quality in a gas–solid fluidized bed for fine coal beneficiation. It focuses on optimizing operational parameters to achieve better fluidization, which in turn improves the efficiency of coal separation and processing (Zhou et al. 2019). The study investigates how particle size, shape, and density affect the performance of an air fluidized bed in dry coal beneficiation. It examines the influence of these factors on the efficiency of coal separation, providing insights into optimizing bed conditions for improved beneficiation outcomes (Chikerema and Moys 2012). One study investigated the de-mixing characteristics of fine coal in an air dense medium fluidized bed, while another concentrated on optimizing a similar separator for high-ash non-coking Indian coal. Collectively, these studies provide important insights into enhancing fluidized bed coal beneficiation technologies and refining the separation process (Mohanta et al. 2013a, b; Zhao et al. 2016).

Studies have examined various aspects of fluidized bed coal beneficiation. The paper evaluates a dense-medium gas-solid fluidized bed separator for the dry beneficiation of high-ash coarse coal. It reports a significant reduction in ash content, with up to a 20% decrease in ash and a 15% increase in the quality of the cleaned coal. The study highlights the separator's effectiveness in enhancing separation efficiency, achieving a separation performance with an overall yield improvement of 10% (He et al. 2016c). The study predicted the position of coal particles in an air dense medium fluidized bed system, demonstrating an accurate particle distribution prediction with an error margin of less than 5%. It also quantified how operational parameters affect particle positioning, showing a 12% improvement in separation efficiency under optimized conditions (Prusti et al. 2015). The study explored a modularized dry coal beneficiation technique using gas-solid fluidized beds, resulting in up to a 20% reduction in ash content and a 15% improvement in coal quality. The modular approach also enhanced operational flexibility and overall efficiency in coal upgrading (Yue-min et al. 2011). The study used a TFM-DEM hybrid model to analyse the impact of operational parameters on particle segregation in a fluidized bed, achieving a 15% increase in segregation efficiency with optimized conditions. Additionally, it investigated the effects of fine coal accumulation, finding that it reduced separation efficiency by up to 10%, underscoring the importance of managing fine coal in the system (Wang et al. 2015b, c). A magnetite particle surface attrition model was developed for dry coal beneficiation in a dense phase fluidized bed. The model showed that controlling surface attrition improved particle durability, leading to a 15% increase in beneficiation efficiency and a 10% reduction in magnetite loss (Zhang et al. 2014).

The study utilized the kinetic theory of granular flow to examine gas-solid interactions in coal beneficiation fluidized beds. It found that optimizing gas flow rates and bed conditions could enhance separation efficiency by up to 18% and reduce energy consumption by 12%, offering valuable insights into improving fluidized bed technologies for coal beneficiation (Wang et al. 2013). The study on dry beneficiation of coarse coal using an air dense medium fluidized bed (ADMFB) quantified the efficiency of coal separation by examining the effects of air flow rates, medium density, and particle size distribution. Optimal air flow rates, typically between 0.8 and 1.2 m per second, combined with medium densities ranging from 1.4 to 1.8 g per cubic centimetre, significantly improved separation efficiency. The ADMFB process achieved a clean coal yield of approximately 80–85%, with a reduction in ash content of up to 30%. These results demonstrate the ADMFB's effectiveness in enhancing coal quality and efficiently removing impurities (Zhenfu et al. 2002).

The study on dry beneficiation and cleaning of Chinese high-ash coarse coal using a dense-medium gas-solid fluidized bed separator evaluated the impact of operating conditions on coal separation performance. By optimizing parameters such as medium density (ranging from 1.5 to 1.9 g per cubic centimetre) and airflow rate (0.9 to 1.1 m per second), the process achieved significant improvements in coal quality. The separation process resulted in a reduction of ash content by up to 40% and an increase in clean coal yield to approximately 75%. These findings underscore the effectiveness of the dense-medium fluidized bed separator in enhancing the quality of high-ash coal through precise control of operational variables (He et al. 2016b).

The Eulerian–Eulerian multiphase model, combined with the Kinetic Theory of Granular Flow (KTGF), was employed to simulate the dynamic behavior of the fluidized bed. The simulation results indicated that optimal beneficiation occurred at a superficial gas velocity of 1.8 to 2.0 times the minimum fluidization velocity, with a dense medium particle size range of $-150+106$ µm (Prasad et al. 2025).

The review on the development of air dense medium fluidized bed (ADMFB) technology for dry coal beneficiation highlights the significant advancements and outcomes achieved in this field. The review emphasizes that the ADMFB technology has effectively improved the separation efficiency of coarse coal by optimizing parameters such as particle size, bed height, and medium density. Key outcomes include a notable reduction in ash content and enhanced clean coal yield, with studies reporting up to a 30% reduction in ash and a 70% increase in clean coal recovery. The review concludes that ADMFB technology offers a promising solution for high-efficiency, dry coal beneficiation, particularly for high-ash and coarse coal types (Sahu et al. 2009).

The study on dry beneficiation of high-ash non-coking coal using an air dense medium fluidized bed (ADMFB) demonstrates significant improvements in separation efficiency. The research finds that by optimizing parameters such as air flow rate and bed density, the ADMFB effectively reduces ash content in the coal. Specifically, the study achieved a reduction in ash content of up to 25% while maintaining a high recovery rate of clean coal. The findings underscore the potential of ADMFB technology to enhance the quality of high-ash non-coking coal, making it more suitable for energy applications and improving overall coal utilization efficiency.

The study on the air dense medium fluidized bed (ADMFB) for dry beneficiation of coal highlights several key findings. The technology achieved an average ash reduction of 15–25% in high-ash coal, with separation efficiency ranging from 85% to 90%. The research identified critical technological challenges, including maintaining stable fluidization and optimizing air and medium flow rates. Specific challenges include ensuring consistent medium density and particle size distribution, which are crucial for achieving high-quality separation. The study underscores the potential of ADMFB technology while emphasizing the need for further advancements to address these challenges effectively (Mohanta et al. 2013b).

The review on dry beneficiation of coal provides a comprehensive overview of various technologies and their performance metrics. It reports that dry beneficiation methods, particularly air dense medium fluidized beds, have achieved significant improvements in coal quality, with reductions in ash content ranging from 10% to 30%. The review highlights advancements in process efficiency, noting that modern technologies can achieve separation efficiencies of up to 90%. Additionally, it identifies key challenges, such as maintaining consistent fluidization and optimizing operational parameters, which are critical for enhancing the effectiveness of dry beneficiation methods (Dwari and Rao 2007).

The study on dry beneficiation of coal presents key findings on early methods for improving coal quality without using water. It demonstrates that techniques such as air classification and fluidized beds can reduce coal ash content by over 20%. The research highlights the effectiveness of these dry processes across different coal types and emphasizes the importance of specific operational parameters to achieve optimal separation efficiency. This approach not only enhances coal quality but also addresses environmental concerns associated with water usage in coal preparation (Lockhart 1984). Geldart's work on gas fluidization provides valuable insights into the behaviour of particles in fluidized beds. The studies reveal that particle size and size distribution significantly influence fluidization characteristics. Geldart categorized particles into four groups based on their fluidization behavior, noting that finer particles generally exhibit more stable and uniform fluidization compared to coarser ones. The research also highlights how the distribution of particle sizes affects the overall efficiency of the fluidized bed, with more uniform size distributions leading to better fluidization performance. These observations underscore the critical role of particle characteristics in optimizing the design and operation of fluidized bed systems (Geldart 1973).

A recent study employed the Box–Behnken design and response surface methodology (RSM) to optimize flotation parameters such as collector concentration, pulp density, and frother concentration for maximizing clean coal recovery. The results indicated that these parameters had a significant influence on coal quality and yield. Under the optimized conditions, clean coal with 18% ash and yields of up to 39.72% were achieved, with deviations from the predicted values remaining below 2% (G & Meikap 2024).

Fig. 1 Coking Coal from Bastacolla Coal Mine

The present work design and optimization of a batch-scale gas-solid fluidized bed separator by employing CFD for a parametric study, and subsequent processing with a froth flotation method. This study aims to:

1. Develop an efficient dry beneficiation process to reduce the ash content in coking coal, making it suitable for steel-making and other industrial applications.
2. Provide an environmentally friendly and cost-effective alternative to the limitations of traditional wet processing.
3. Enhance the understanding of the air dense medium fluidized bed (ADMFB) separation mechanism through comprehensive CFD analysis, leading to optimized operational parameters and improved separation efficiency.
4. Attempt fine coal processing using a froth flotation process with both conventional and synthetic reagents to achieve the target ash content of 17–18%.

Materials and methods

The coal sample (-100 mm) from the Ena Open Cast Project in the Kusunda area was collected (Fig. 1) for further characterization and processing. The as-received coal sample underwent coning and quartering method followed by screening into different size fractions for weight and ash analysis. A representative sample of the as-received coal sample was analyzed using various methods to determine its characteristics, including proximate analysis, ultimate analysis, Gross Calorific Value (GCV), petrography, Low-Temperature Gray-King (LTGK), Free Swelling Index (FSI), X-Ray diffraction (XRD), X-Ray Fluorescence (XRF) and washability analysis.

Dry processing of crushed coal sample (reduced to 50 mm) was conducted, varying process parameters such as bed height, medium size, and air flowrate. The responses measured included ash content of the products, recovery of combustibles, ash rejection and efficiency. Further processing involved the pre-concentrate (-50+6 mm) produced from dry separator, along with natural −6 mm fraction, which was crushed down to 0.5 mm for processing in a froth flotation cell. Different reagents were used in froth flotation experiments, including kerosene, diesel, Synthetic reagent as collectors and Methyl Isobutyl Carbinol (MIBC) and Synthetic reagent as frothers. A 2-litre capacity laboratory scale froth flotation cell was used for this study. The detailed methodology is illustrated in Fig. 2.

Experimental set up

The experimental set up used for the study is illustrated in Fig. 3. It consists of four parts: an air supply; flow control devices, a plexiglass cylindrical gas–solid fluidized bed of diameter 200 mm and height of 600 mm and data measurement equipment; compressed air, generated by a fan blower and passed through an air buffer tank, flows into the bed through a gas distributor located at the bottom. The gas distributor having an aperture ratio of 30% consists of a perforated stainless-steel plate. Differential pressure transducers are arrayed vertically along the side wall and the pressure drop data are measured using data logger connected with PC. The bed height can be measured using a ruler fixed on the bed wall. The moving bubbles are observed manually. To perform an experiment, the fan blower was turned on. Then, a certain amount of the magnetite powder was fed into the fluidized bed to be fluidized by the fluidizing gas. A fluidized bed having a specific density and height was then formed. The hydrodynamics of the Geldart B particles were examined in detail under various operating conditions.

Experimental method

Air is introduced from the bottom of the separator through a distributor plate, creating an upward flow that fluidizes the medium particles. The fluidized bed behaves like a liquid, with particles able to move freely within it. As the medium particles are fluidized, a density gradient is established within the bed. Particles with higher density settle at the bottom, while lighter particles are suspended higher up. The raw material is fed into the fluidized bed. Particles with a density higher than the fluidized medium sink and are discharged as the underflow (rejects), while particles with a lower density float and are collected as the overflow (clean coal).

Unlike wet beneficiation methods, ADMFB does not require water, making it suitable for arid regions and reducing the need for water treatment facilities. The dry separator can handle large feed sizes and achieve high separation efficiency. It also reduces water consumption and the associated environmental impact of slurry disposal.

Results and discussion

Material characterization

The raw coal samples were primarily analyzed for proximate analysis to determine moisture content, volatile matter, and ash content according to ASTM D3173, D3174, and D3175

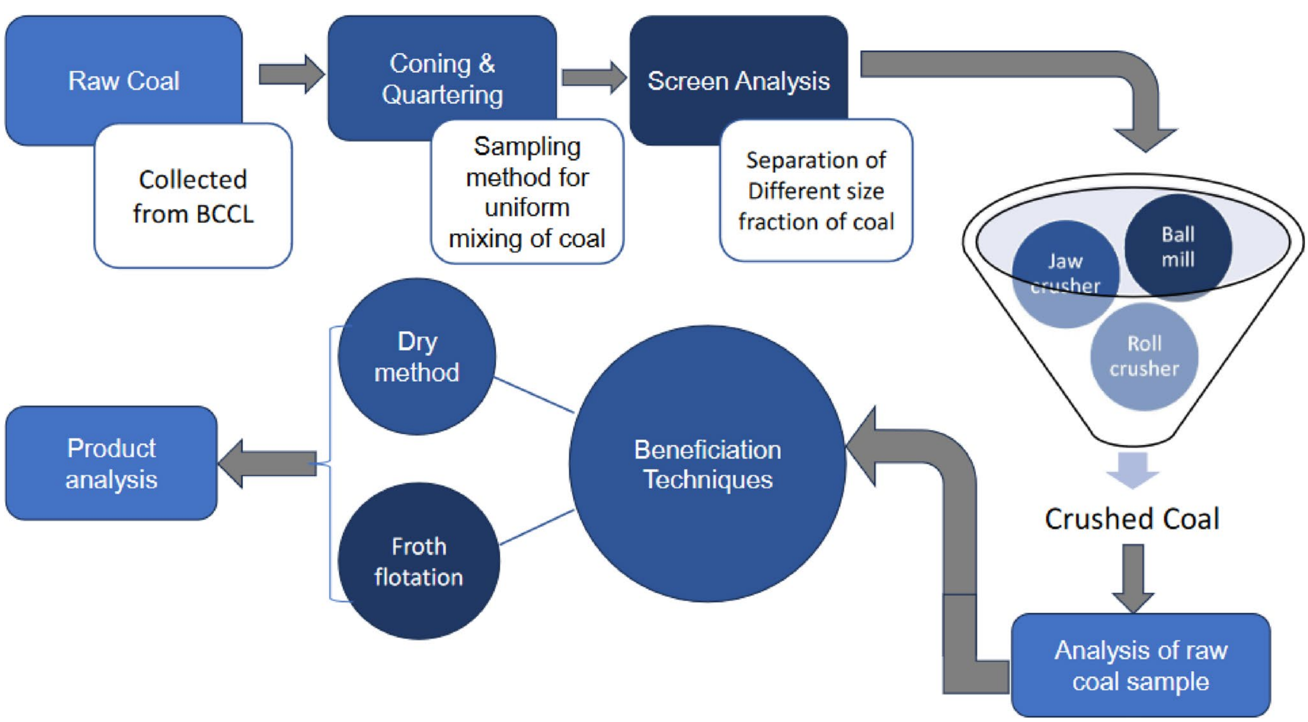


Fig. 2 Working methodology for processing of Bastacolla coal sample

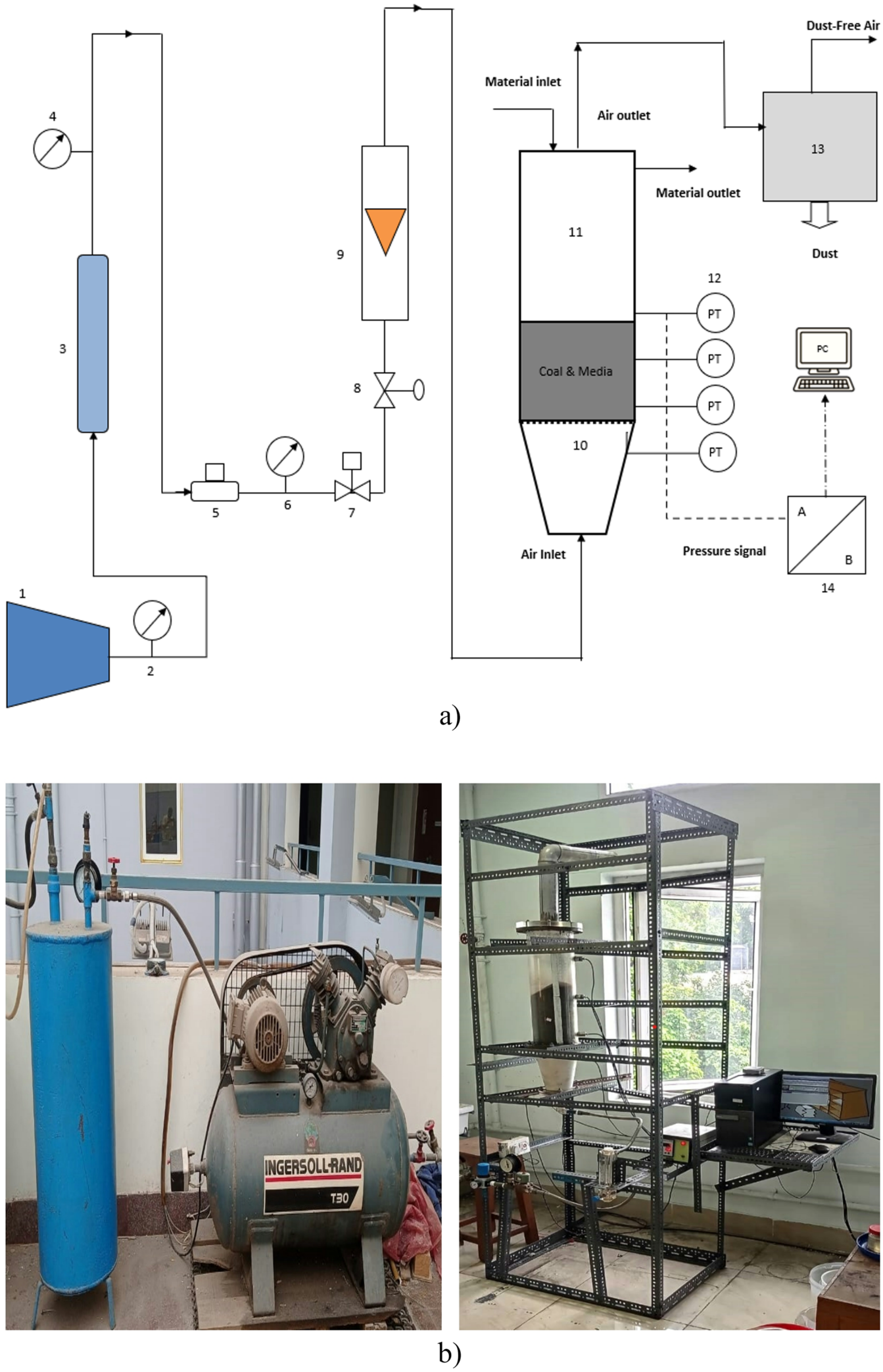


Fig. 3 **a**) Schematic diagram of Gas-solid fluidized bed apparatus. (1) Air compressor; (2) Pressure gauge; (3) Air buffer tank; (4) Pressure guage; (5) Pressure regulator; (6) Pressure guage; (7) Solenoid valve; (8) Globe valve; (9) Rotameter; (10) Distributor; (11) Fluidized bed chamber; (12) Pressure transducer; (13) Dust collector; (14) Data logger. **b**) Experimental apparatus

standard techniques, respectively. The fixed carbon content was determined by difference. For elemental analysis, the samples were analyzed using a CHNS/O analyzer (EL Vario MICRO Cube, Elementar TM) following the ASTM D5291 standard technique. The free oxygen content of the samples was calculated by difference. Additionally, the GCV of the coal samples was estimated using a bomb calorimeter under equilibrated conditions (temperature = 40 °C and relative humidity = 60%). The analysis results of the raw coal samples are recorded in Table 1.

A representative portion of the head sample (approximately 500 g) was taken for petrographical analysis. Using

Table 1 Characterization of coal sample

Bastacolla OCP	
Proximate analysis of coal on air-dry basis (wt%)	
Moisture content	0.98
Volatile matter	14.31
Fixed carbon	40.69
Ash	44.31
Gross Calorific value ((Kcal/kg))	4203
Ultimate analysis of coal on air-dry basis (wt%)	
C	45.50
H	3.54
N	0.85
S	0.46
O	49.65
Free Swelling Index	1
Low Temperature Grey King	E

Table 2 Maceral composition

Coal used	Vitrinite %	Inertinite %	Liptinite %	Mineral Matter %
Bastacolla OCP	35.20	15.40	8.80	40.60

the coning and quartering method, about 200 g of the sample was selected for mounting and polishing. The sample was crushed to below 1 mm, and polished mounts were prepared using epoxy resin and hardener. Coal petrography was conducted to study the organic and inorganic phases of coal, including maceral and mineral identification, their textural relationships, mode of occurrence, distribution, and reflectance. This was done using an advanced polarizing microscope (DM4500, Leica, Germany) following the IS-9127 standard. Microscopic analysis revealed that the coal from Bastacolla OCP has a high ash content (mineral matter 40.60%). The modal analysis provides an approximate idea of the maceral distribution in the coal, with vitrinite at 35.20%, inertinite at 15.40%, and liptinite at 8.80%. The maceral constituents are detailed in Table 2.

The size and size-wise ash analysis was carried out by taking the RoM coal (as received) to different top-size ranges 100 mm, 50 mm, 25 mm, 13 mm, 6 mm, 3 mm, 0.5 mm and pan and then screening the material over a nest of sieves to obtain 100% passing that screen, in the laboratory. Further, each size fraction material was subject to further screening using lab screens and size-wise ash determinations. The fraction wise weight and Ash distribution is depicted in Fig. 4.

The as received coal was crush down to 50 mm using hammer crusher. The crushed coal was screened to different top-size ranges such as 50 mm, 25 mm, 13 mm, 6 mm, 3 mm, 0.5 mm and pan and then screening the material over a nest of sieves to obtain 100% passing that screen, in the laboratory. Further, each size fraction material was subject to further screening using lab screens and size-wise ash determinations. The detailed Size & Size-wise ash analysis of Raw coal crushed to 50 mm are presented in Fig. 5.

The as received coal samples was crush down to 25 mm using hammer. The crushed coal was screened to different top-size ranges such as 25 mm, 13 mm, 6 mm, 3 mm, 0.5 mm and pan and then screening the material over a nest of sieves to obtain 100% passing that screen, in the laboratory. Further, each size fraction material was subject to further screening using lab screens and size-wise ash determinations. The detailed Size & Size-wise ash analysis of Raw coal crushed to 25 mm are presented in Fig. 6.

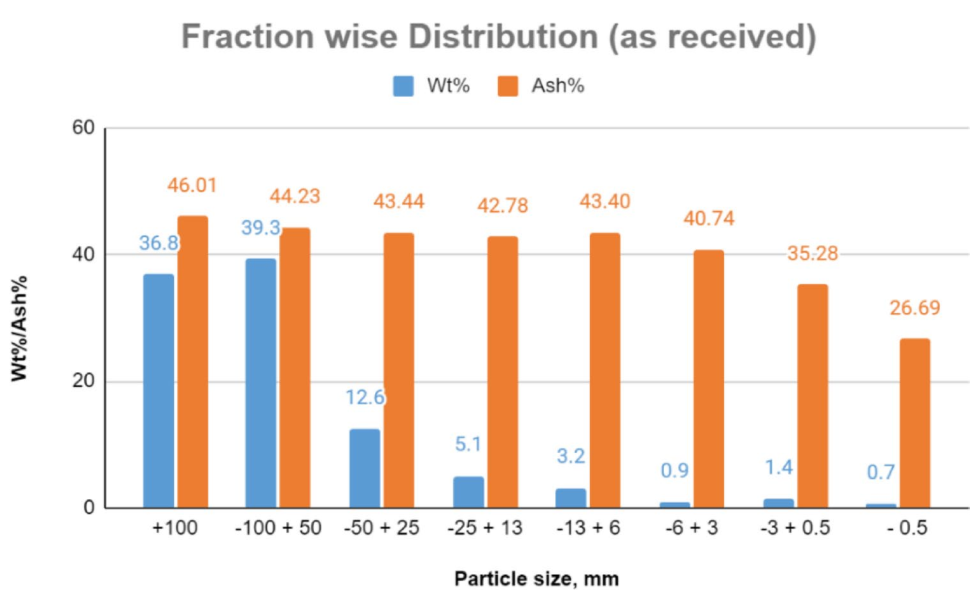


Fig. 4 Fraction wise Distribution of Weight and Ash (as received)

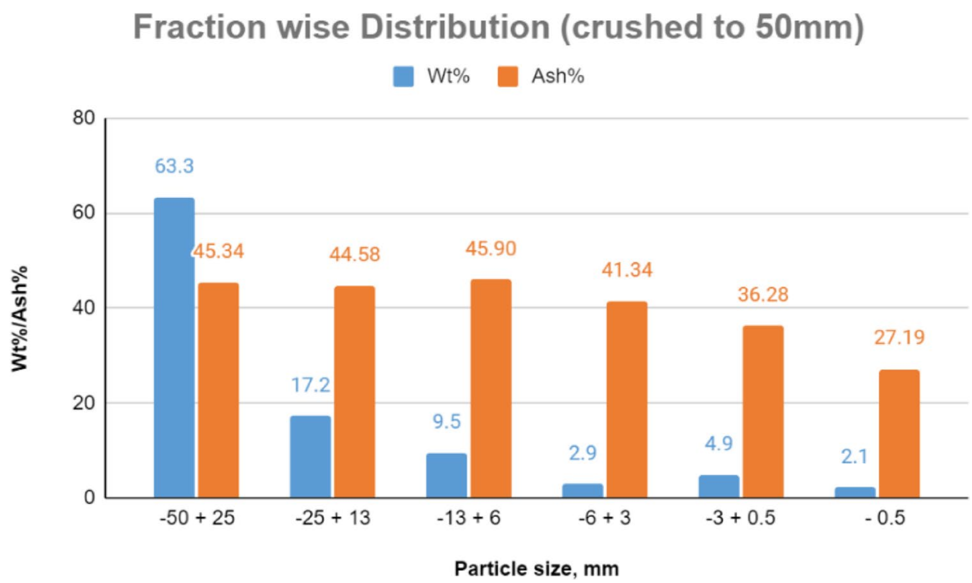


Fig. 5 Fraction wise Distribution of Weight and Ash (crushed to 50 mm)

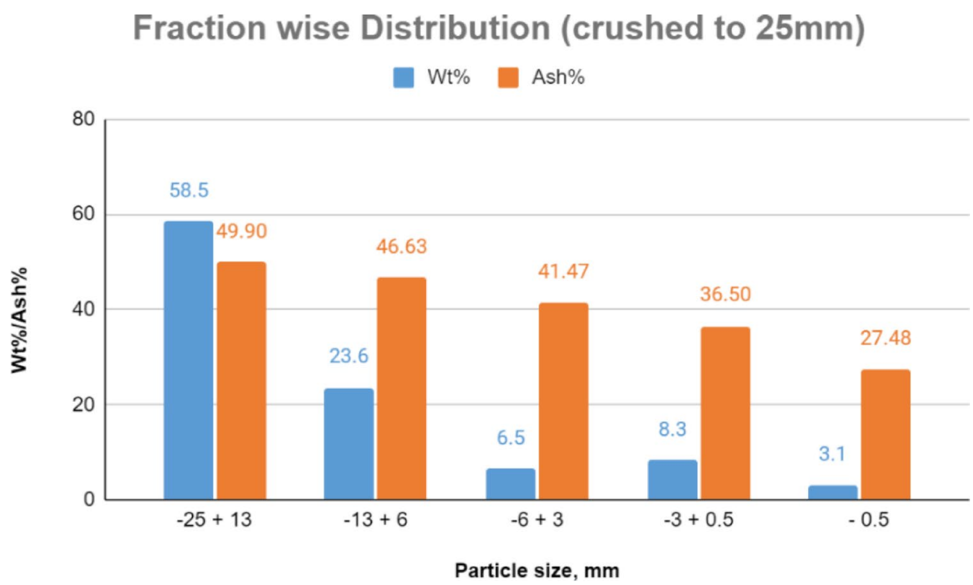


Fig. 6 Fraction wise Distribution of Weight and Ash (crushed to 25 mm)

Sink & float analysis

The as received coal sample crushed down to 50 mm and the crushed coal screened/deslimed to produce two fractions i.e. -50+0.5 mm and −0.5 mm for further analysis. The chemicals such as Benzene (C_6H_6), Tetrachloroethylene (C_2Cl_4) and Bromoform ($CHBr_3$) were used for conducting sink & float analysis having specific gravity of 0.8765 g/cc, 1.622 g/cc and 2.63 g/cc respectively. The solutions of different specific gravity 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9 were prepared using the above chemicals for washability analysis. The products recovered from the above test are air dried, weighment of each fraction and pulverized to 72 mesh for ash analysis. The washability curves of -50+0.5 mm and −50+6 mm size fraction were drawn based on results of sink-float analysis and is presented in Figs. 7 and 8.

The 50 mm coal sample crushed down to 25 mm and the crushed coal screened to different size fractions such as -25+13 mm, -13+6 mm, -6+3 mm, -3+0.5 mm and −0.5 mm for further analysis. The size fraction of -25+6 mm is processed for washbility analysis. Chemicals such as Benzene (C_6H_6), Tetrachloroethylene (C_2Cl_4) and Bromoform ($CHBr_3$) were used for conducting washability analysis having specific gravity of 0.8765 g/cc, 1.622 g/cc and 2.63 g/cc respectively. The solutions of different specific gravity 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9 were prepared using the above chemicals for washability analysis. The products recovered from the above test are air dried, weighment of each fraction and pulverized to 72 mesh for ash analysis. The washability curves of -25+6 mm size fraction were drawn based on results of sink-float analysis and is presented in Fig. 9.

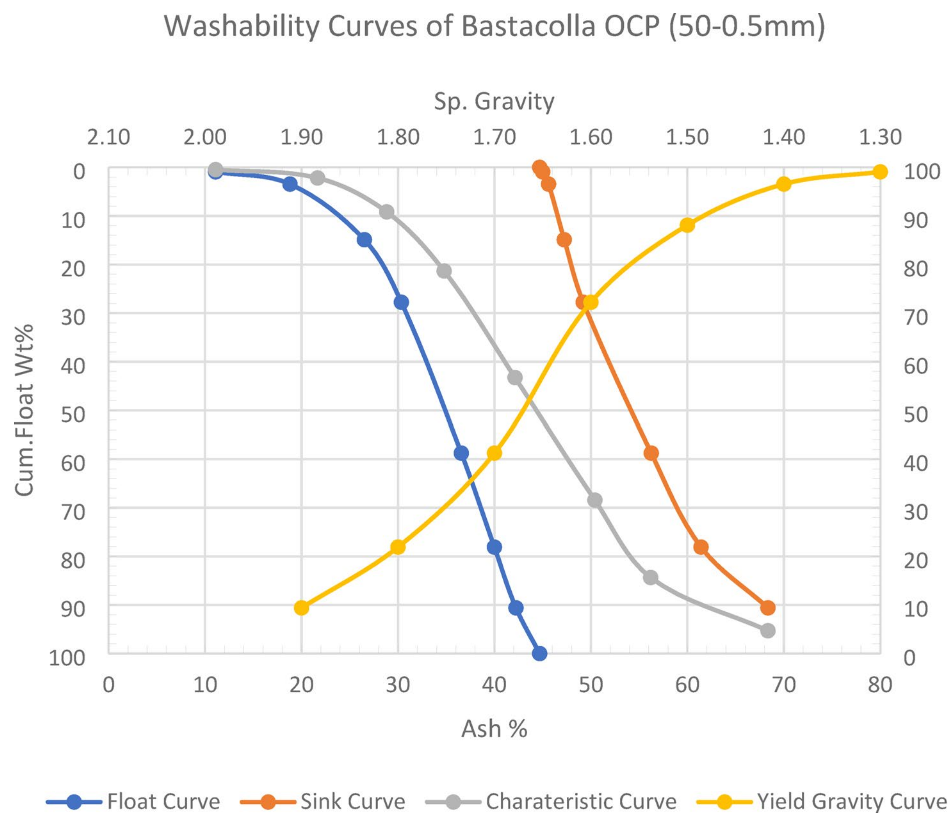


Fig. 7 Sink float analysis of Bastacolla OCP Coal crushed to 50 mm

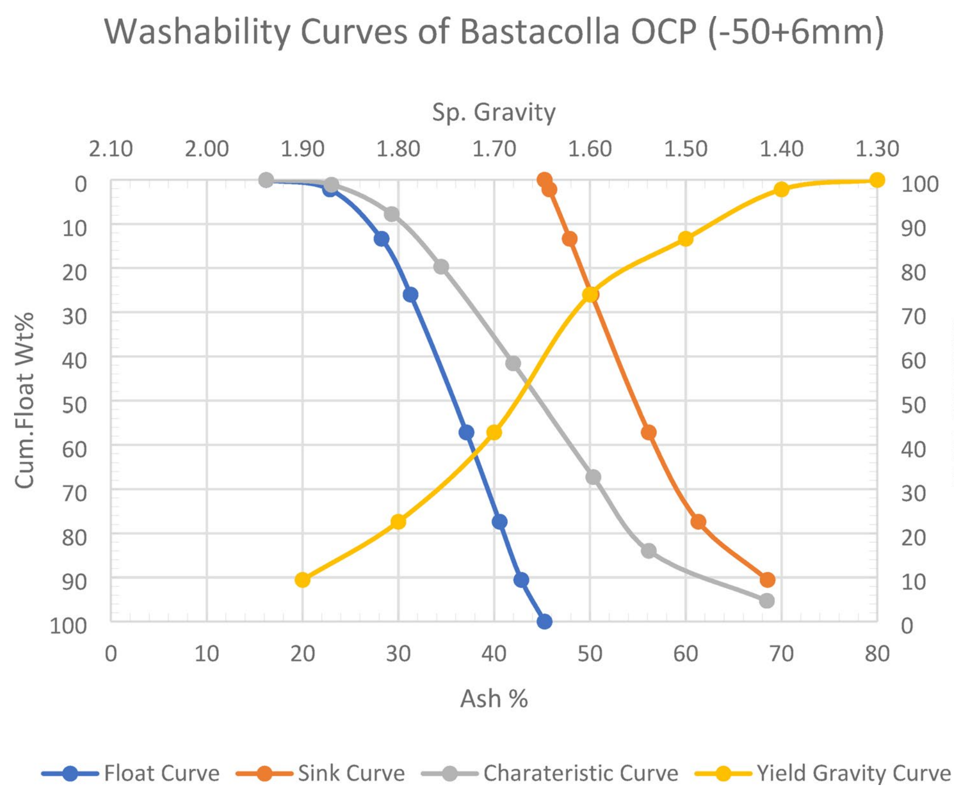
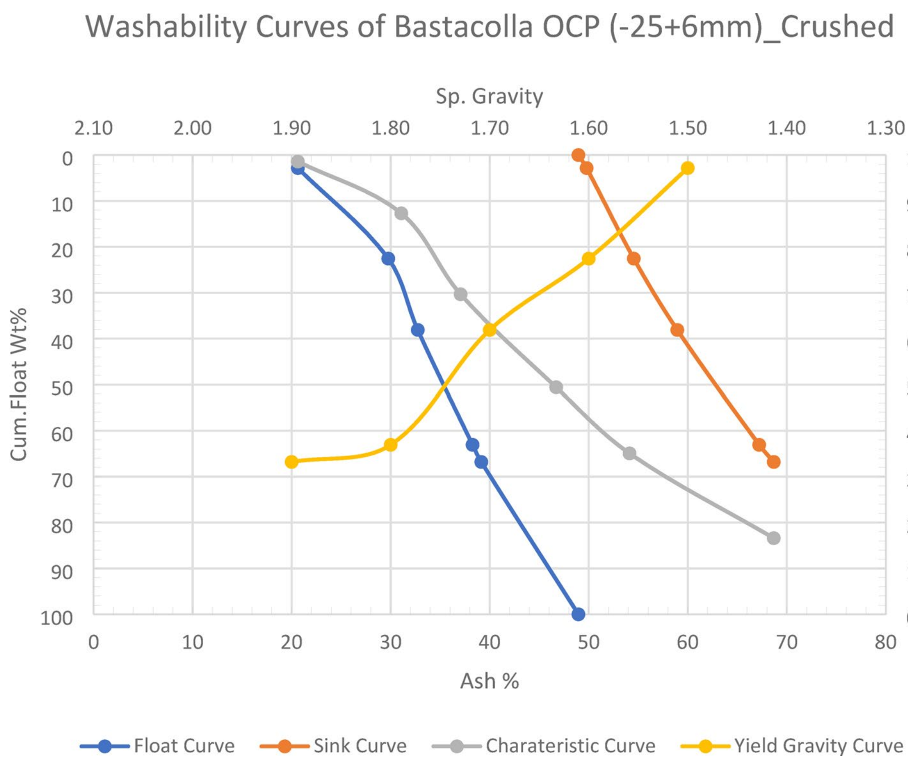


Fig. 8 Sink float analysis of Bastacolla OCP Coal (-50 + 6 mm)

Fig. 9 Sink float analysis of Bastacolla OCP Coal (-25 + 6 mm) crushed



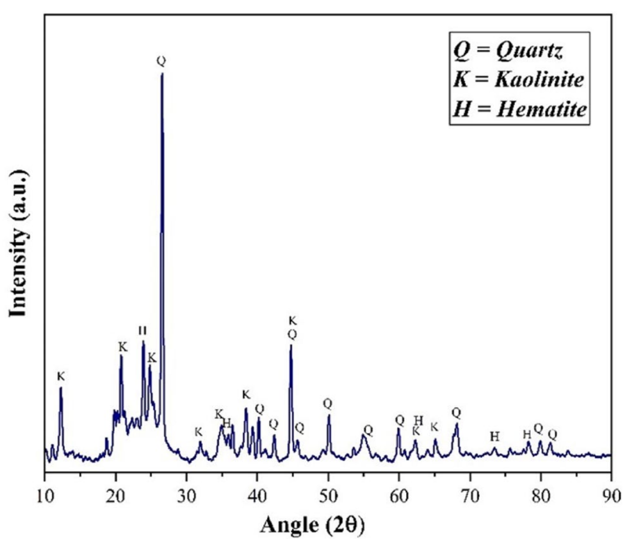


Fig. 10 XRD images of Bastacolla OCP

XRD analysis

The as received coal sample was crushed and pulverized to 72 mesh taken for the analysis. X-ray Diffraction (XRD) was performed on the coal samples using PANalytical High-Resolution X-ray Diffractometer and a Cu k-alpha radiation from 10 to 90°, 2θ with a 0.02 step and are plotted into Origin lab software to investigate the major mineral associate to the coal samples, identifying the peaks. Each scan is processed using standard JCPDS XRD search–match programs for the identification of mineral phases present, namely quartz (JCPDS 00-046-1045), kaolinite (JCPDS 00-005-0143), and hematite (JCPDS 33–0664). The major mineral peaks correspond to quartz and kaolinite mineral groups, while the moderate/low mineral peaks correspond to hematite mineral groups as shown in Fig. 10.

XRF analysis

The evaluation of the energy dispersive X-Ray Fluorescence (XRF) spectroscopy method, for the analysis of major, minor and trace elements present in the mineral matter of coal, using an apparatus with sources of radioisotope elements, is described. From the Oxide Compound analysis at Fig. 11, we can see the concentration of the silicon dioxide (silica) is the highest in the coal samples followed by aluminium oxides and iron oxides. From the Elemental XRF analysis at Fig. 12, we can see that the concentration of the oxygen element is highest in the coal sample followed by aluminium, silicon and iron. And from literature survey also we observed that generally coal consists of the impurities of the aluminium, silicon and iron.

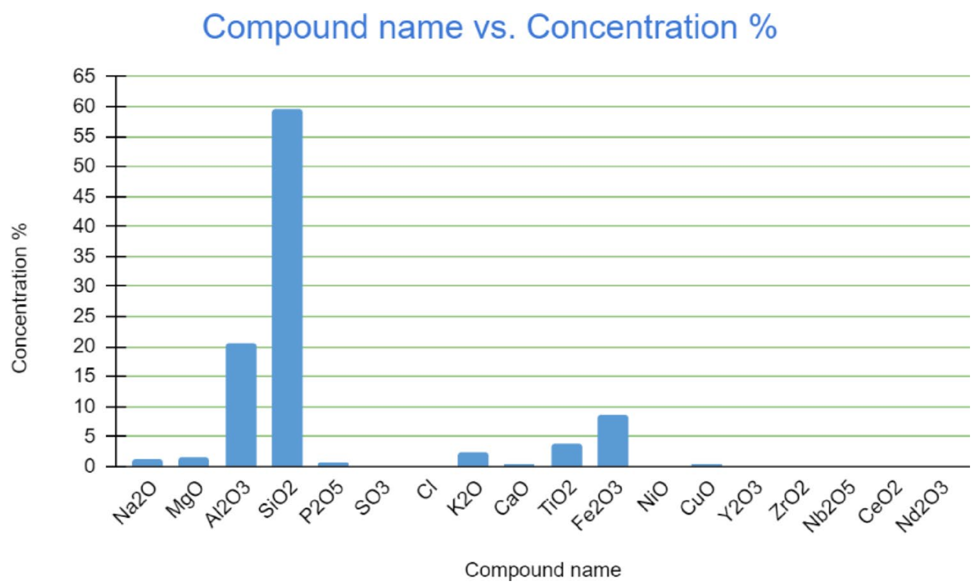


Fig. 11 XRF analysis (Oxide form) of Bastacolla OCP

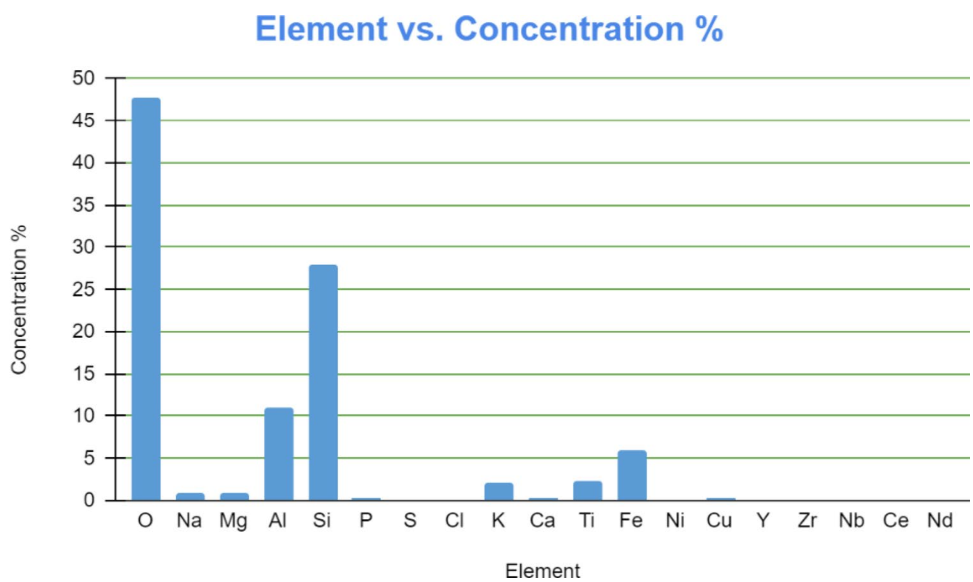


Fig. 12 XRF analysis (Element form) of Bastacolla OCP

Study of ADMFB parameters using CFD

The two-dimensional geometry was created on an XY plane using the Design Modeler module in ANSYS Fluent 2022, with dimensions of 200 mm by 1200 mm and featuring a cylindrical solid surface body. At Fig. 13 shows that the geometry includes four edges, four vertices, and one face. The solid surface body was then prepared for mesh generation, utilizing standard meshing with an element size of 5.0 mm in a linear order. This meshing resulted in a total of 9,881 nodes and 9,600 elements **(**ANSYS 2022**).**

Once the solid surface body and meshing were completed on the 2D XY plane, the physical setup phase began, which involved selecting the solver, defining models for different phases, setting material properties, and establishing boundary conditions. A pressure-based solver was selected for the cylindrical fluidized bed system, which operates on density or differential pressure to effectively separate coal and shale in the presence of magnetite powder. The system included gas/air as the primary phase and solid/magnetite powder as the secondary phase in granular form. The Eulerian model was employed for both phases, with the Syamlal-O'Brien model selected for gas-solid interactions in the fluidized bed, considering a minimum fluidization velocity of 0.06 m/s and an assumed void fraction of 0.4 (Syamlal et al. 1994). Material properties were defined as follows: gas density of 1.225 kg/m³ and viscosity of 1.7894×10^{-5}Pa·s, and solid density of 4950 kg/m³ with the same viscosity. Boundary conditions specified included the inlet gas velocity, outlet pressure profile, and the operation of the gas-solid fluidized bed based on gravity and specified density. The solution methods chosen were pressure-based coupling, the

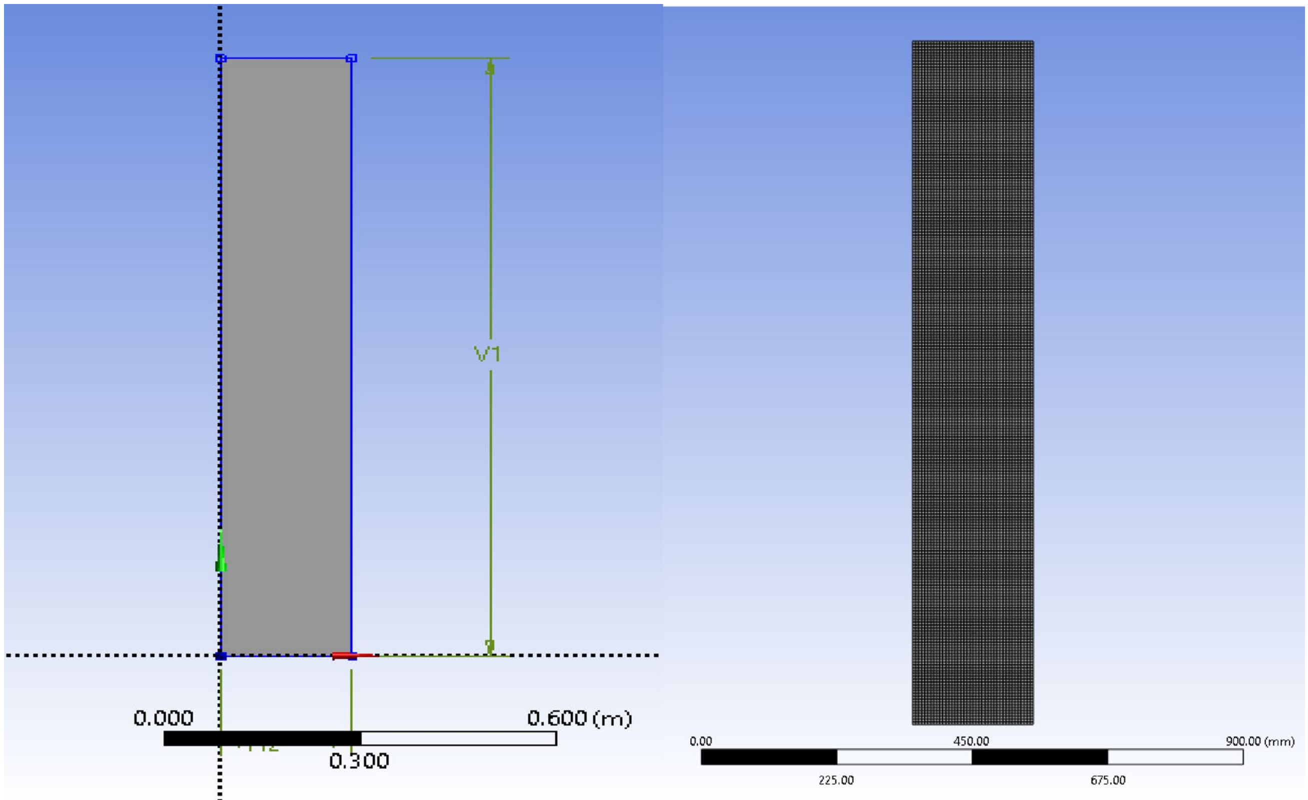


Fig. 13 Geometry formation and Mesh generation in 2D XY plane

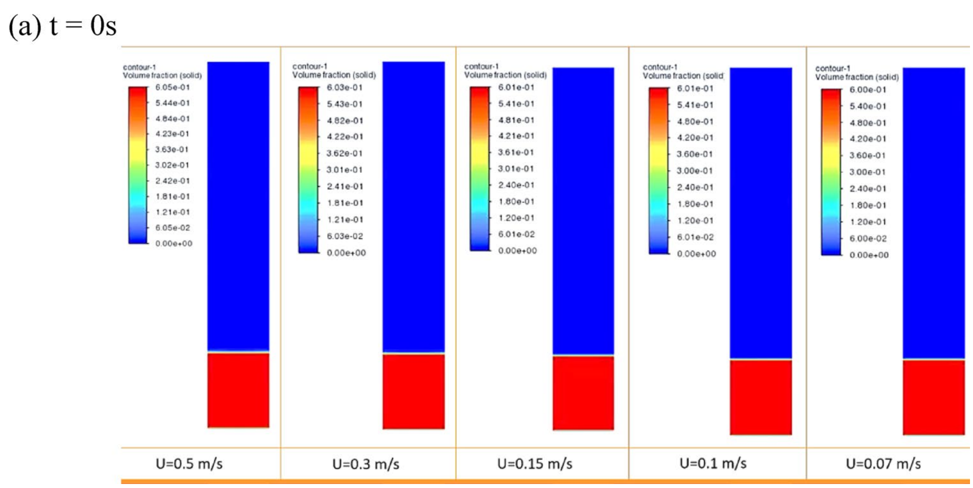


Fig. 14 Volume fractions of solids at different velocity of gas at time 0s

least squares gradient method, second order for pressure, first order upwind for momentum and volume fractions, and second order implicit for transient formulations.

Effect of varying gas Inlet velocity

From the Figs. 14, 15 and 16, initially at t = 0, the bed height is 25 cm and consists of magnetite powder with a constant density and viscosity of the mixture (gas + solid). After t = 0, air is introduced from the spurge at varying gas inlet velocities of 0.5 m/s, 0.3 m/s, 0.15 m/s, 0.1 m/s, and 0.07 m/s.

By varying the inlet gas velocity, we are observing the behavior of the bed density with respect to time to determine the optimum gas inlet velocity for stable operation of the fluidized bed. Higher velocities, such as 0.5 m/s, result in slugging behavior, characterized by the formation of large bubbles and non-uniform flow, as indicated by the presence of many blue regions in the handling area, which signify high voidage and poor flow uniformity.

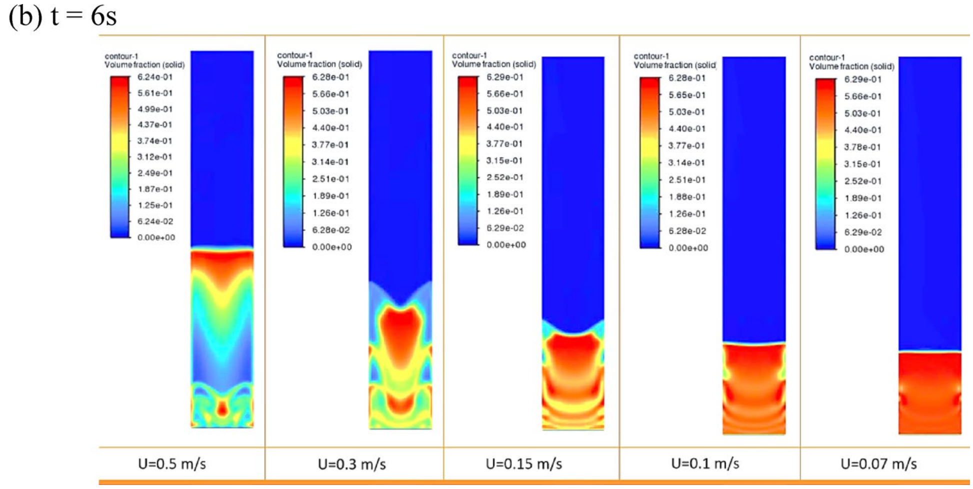


Fig. 15 Volume fractions of solids at different velocity of gas at time 6s

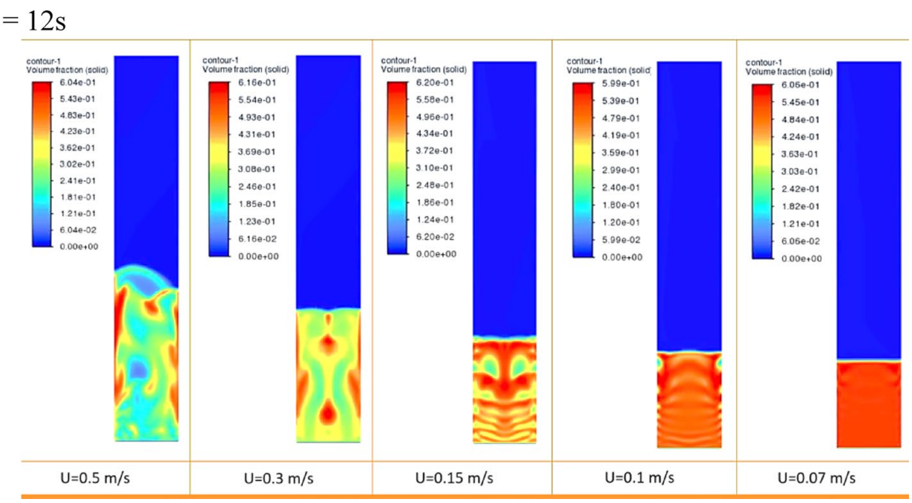


Fig. 16 Volume fraction of solids at different velocity of gas at time 12s

Decreasing the inlet gas velocity leads to a reduction in voidage between solid particles and results in a more uniform flow, which is the desired operating condition for an air dense medium fluidized bed. This adjustment ensures that the bed operates more stably, with reduced slugging and better flow characteristics, aligning with the principles of optimal fluidized bed operation.

From Fig. 17, it is showed the velocity currents in the fluidized bed with respect to different inlet gas velocities. Initially, at higher gas inlet velocities, such as 0.5 m/s, the velocity current profile is wavy and non-uniform. However, with a significant decrease in the inlet gas velocity from 0.5 m/s to 0.07 m/s, the velocity current profile becomes more stable and uniform across the fluidized bed. This transition reflects the typical behavior where higher velocities can induce irregular flow patterns, while lower velocities promote a more stable and uniform flow profile in fluidized beds.

From the contours of the velocity profile at Fig. 17 and velocity magnitude at Figs. 18 and 19, it is observed that a gas inlet velocity of 0.07 m/s and 0.1 m/s represent the optimal operating conditions for uniform fluidized bed performance. At these velocities, the entire fluidized bed operates uniformly, with the velocity profile showing a consistent and stable flow distribution across the bed. This uniform operation is crucial for efficient separation and processing within the fluidized bed, as higher or lower velocities can lead to non-uniform flow patterns and suboptimal performance.

From the pressure contours shown in the Fig. 20, we observe how pressure varies in the fluidized bed with different inlet gas velocities. Initially, at higher gas inlet velocities, such as 0.5 m/s, the pressure is notably high due to the influence of the distributor plate. As the inlet gas velocity decreases to 0.1 m/s and 0.07 m/s, the pressure profile becomes more uniform across the cross-section of the fluidized bed, and pressure fluctuations become more stable with respect to bed height. This indicates that at lower gas inlet velocities, the pressure distribution is more consistent and uniform, which is desirable for stable fluidized bed operation. Lower velocities reduce the turbulence and uneven pressure profiles that can be observed at higher velocities,

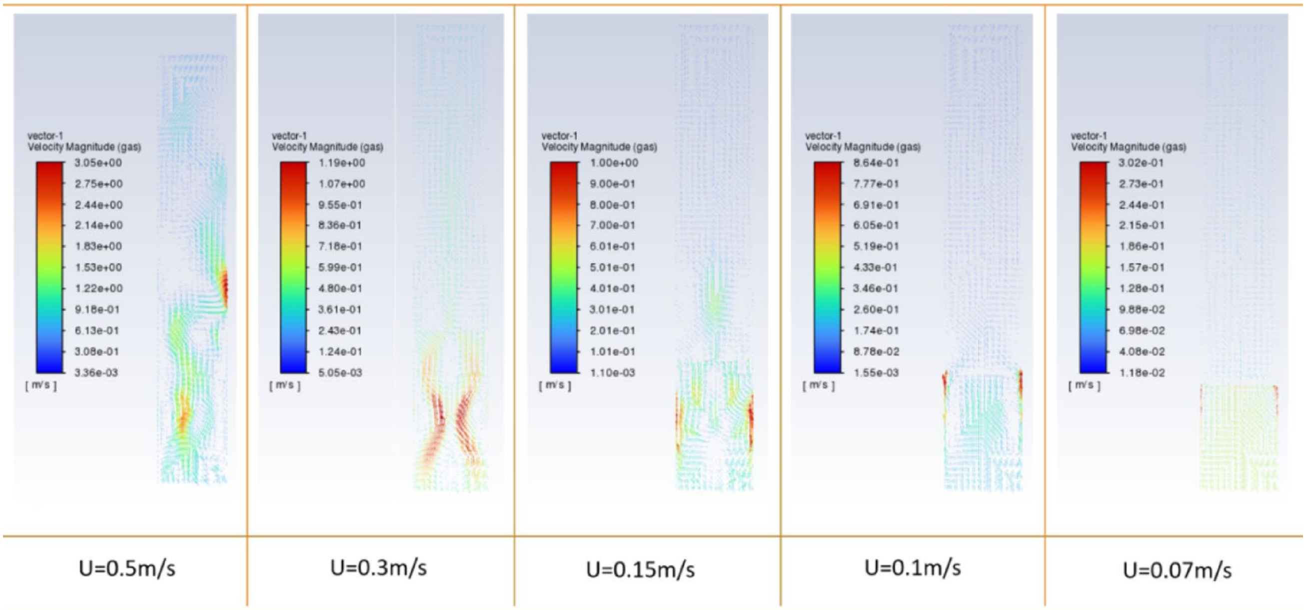


Fig. 17 Velocity Current profile

Fig. 18 Velocity Magnitude of gas

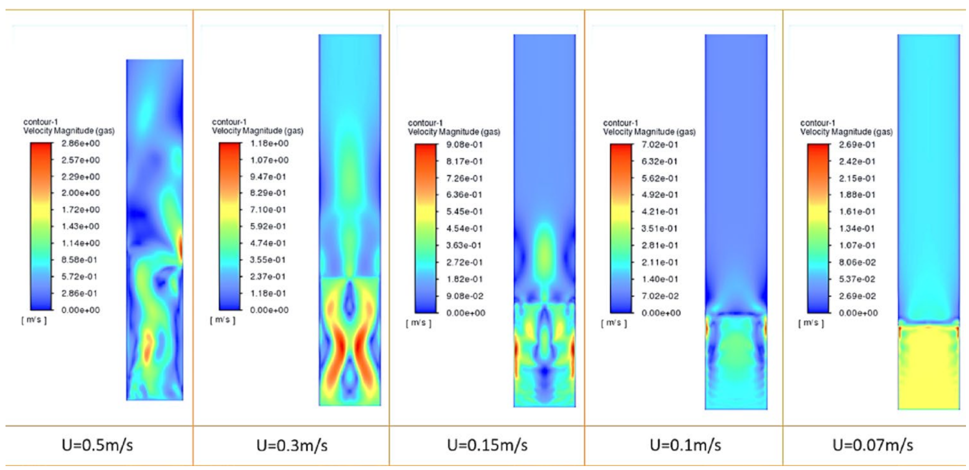
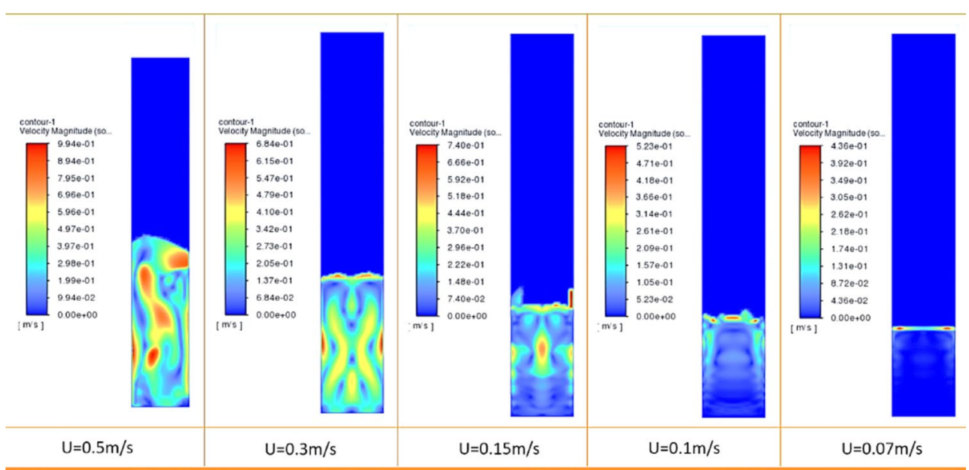


Fig. 19 Velocity Magnitude of Solids



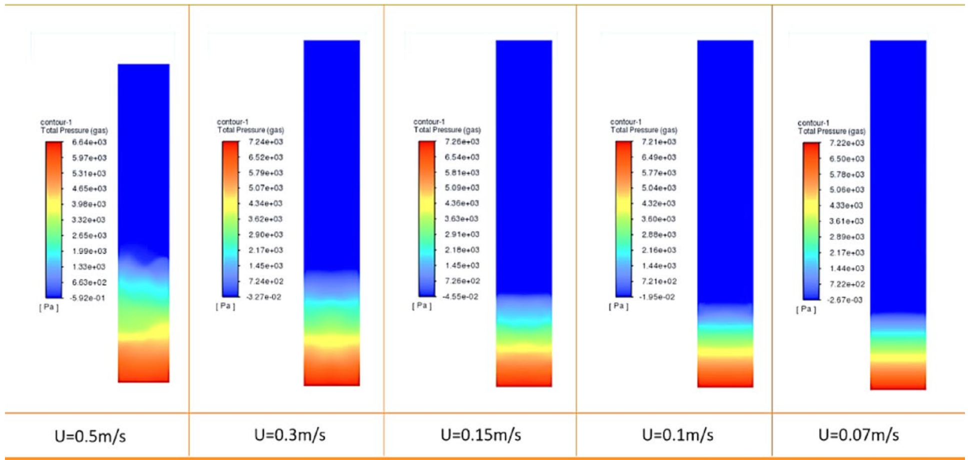


Fig. 20 Pressure Contours

leading to a more stable and efficient operation of the fluidized bed.

Effect of varying gas inlet velocity from 0.31 to 0.1 and 0.5 m/s

From the Fig. 21 (a), it is observed that the bed density or solid fraction profile is consistent across different gas inlet velocities, specifically at 0.31 m/s. However, as the gas inlet velocity increases from 0.31 m/s to 0.5 m/s, noticeable voids or bubbles develop throughout the bed height, leading to bed instability and operational challenges. This instability is evident as higher gas velocities tend to create significant bubble formation, which disrupts the uniformity of the bed and complicates its handling.

Conversely, when the gas inlet velocity is reduced from 0.31 m/s to 0.1 m/s, the bed stability improves, and handling becomes more manageable. The decrease in gas velocity reduces bubble formation and enhances the overall stability of the bed, making it easier to operate under these conditions. Thus, a lower gas inlet velocity of 0.1 m/s is preferable for achieving a more stable and manageable fluidized bed.

Effect of varying bed height

From the analysis of Fig. 22, it is observed that initially, at time $t = 0$, the gas inlet velocity is 0 m/s. As time progresses, with the gas inlet velocity maintained constant at 0.1 m/s, variations in bed density at different heights are examined. The results indicate that at a bed height of 0.35 m, there are noticeable void fractions or slug flow, which signifies instability within the bed. In contrast, at bed heights of 0.15 m and 0.25 m, the bed density profiles show more stable conditions with minimal voidness.

This suggests that at a gas inlet velocity of 0.1 m/s, the bed heights of 0.15 m and 0.25 m are more desirable for stable operation. Conversely, for higher bed heights, operating the bed at a gas velocity lower than 0.1 m/s would be necessary to maintain stability and minimize voids. These observations underscore the importance of optimizing both bed height and gas velocity to achieve efficient and stable fluidized bed operation.

Effect of varying particle diameter

From Fig. 23, it is observed that at $t = 0$, the bed height is set at 25 cm and consists of magnetite powder with constant density and viscosity of the gas-solid mixture. After $t = 0$, air is introduced through the spurge from the bottom of the air dense medium fluidized bed at a fixed gas inlet velocity of 0.1 m/s. The study investigates the behavior of bed density and solid contours across the bed with different particle diameters. For this analysis, three distinct particle sizes were used: 302.423 µm, 209.128 µm, and 115.833 µm. These particle diameters were determined using Malvern particle size analysis, which provides volume mean diameter, surface mean diameter, and arithmetic mean of volume and surface mean diameters.

The observations highlight how varying particle sizes influence the bed density and solid contours within the fluidized bed under constant gas inlet velocity. Larger particles tend to create more pronounced variations in bed density, potentially leading to non-uniformities in the fluidized bed profile, while smaller particles generally result in more stable and uniform bed conditions.

From this analysis, it is observed that as the particle size becomes finer, the bed density becomes non-uniform and tends toward unstable conditions at a constant gas inlet velocity and bed height. Finer particles, due to their smaller size, lead to increased interparticle interactions and voidage, which can result in a less stable fluidized bed profile.

To achieve uniform bed density and maintain stable operation with finer particles, it is necessary to increase the

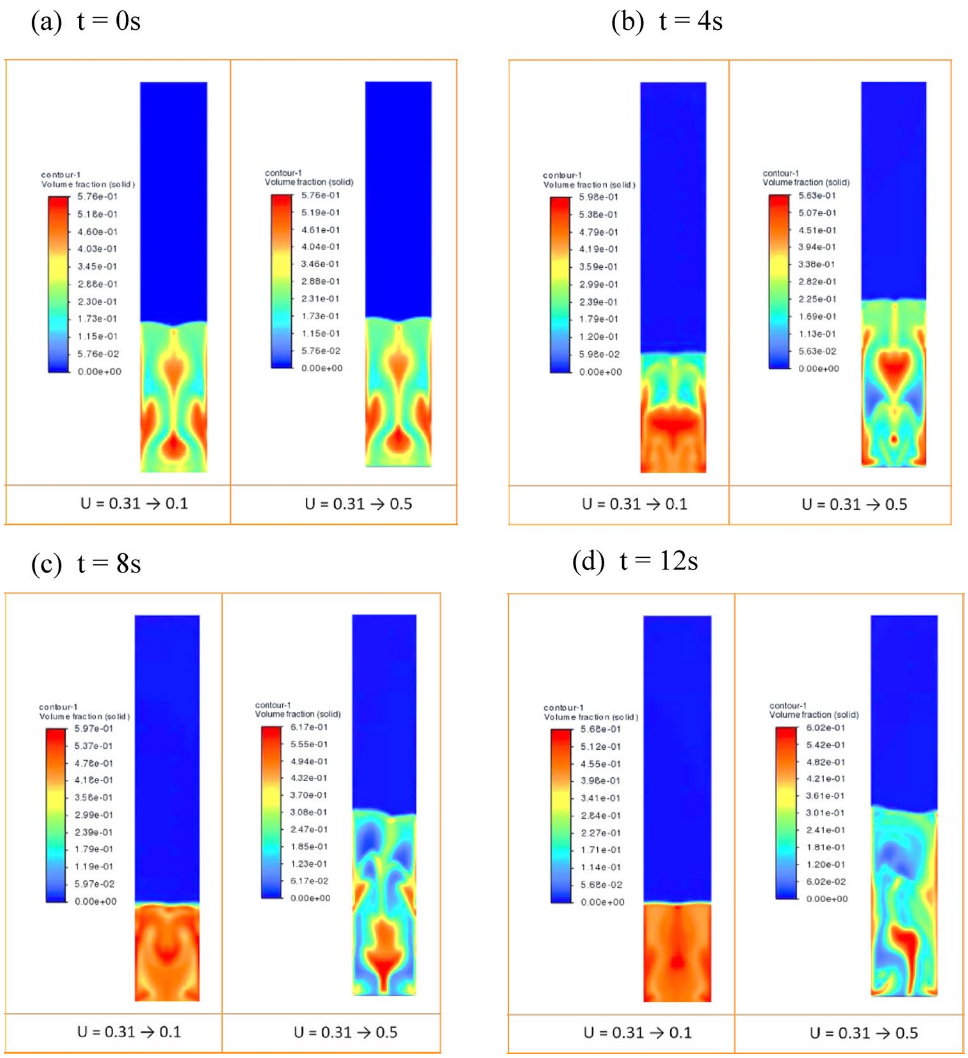


Fig. 21 Void fraction of the bed while Velocity of gas increases and decreases simultaneously at time (**a**) 0s (**b**) 4s (**c**) 8s (**d**)12s

gas inlet velocity. Higher gas velocities help to mitigate the instability by enhancing fluidization and ensuring that the particles remain suspended more effectively. This adjustment helps in achieving a more uniform distribution of particles and stabilizes the fluidized bed.

Dry processing

Based on the parameter study conducted using CFD, the following procedure was implemented for the dry processing of coal samples:

a) The size fractions selected for processing were −50+6 mm and −25+6 mm coal, utilizing an air dense medium fluidized bed separator. Magnetite powder, with a true density of 4700 kg/m³, was used as the dense medium to enhance the separation of coal from impurities. The process commenced with a continuous supply of compressed air at the bottom of the dry separator. This air flow was maintained until the bed reached its superficial gas velocity, surpassing the minimum fluidization velocity. At this point, the bed achieved a steady-state pressure and density profile.
b) Once a constant bed density was established, coal was introduced from the top of the fluidized bed. The bed enabled the stratification of coal particles according to their density. When stratification reached equilibrium, the air supply was turned off.
c) Samples were then collected in layers from top to bottom. Each layer was analyzed separately, with coal and magnetite powder being separated using screening and magnetic separation methods for further analysis. This process ensured the efficient separation of coal from impurities, leveraging the principles of fluidization and density-based stratification.
d Coal samples from each layer were weighed and crushed down to 72 mesh for ash analysis.

The experimental parameters maintained during the study are summarized in Table 3. In Tables 4 and 5 present the

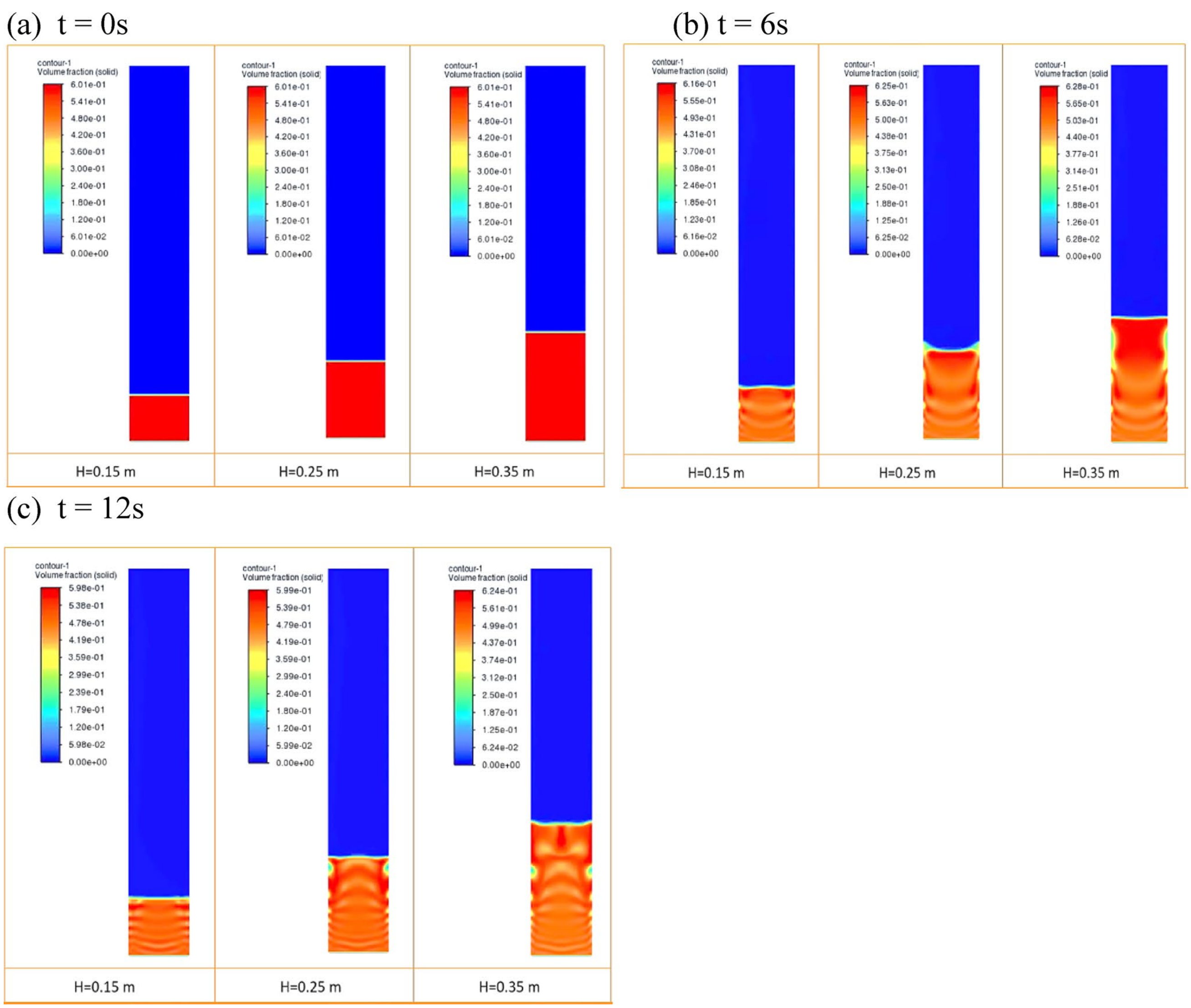


Fig. 22 Volume fractions of solids at different bed height at time (**a**) 0s (**b**) 6s (**c**)12s

consolidated outcomes for the −50+6 mm and −25+6 mm size fractions, along with the natural−6 mm fraction. Table 6 details the float and sink results from the dry processing, distinguishing between clean coal and middlings/sinks. Figure 24 illustrates the partition curves, depicting the efficiency of the separation process on density cuts.

Based on the data from the Table 5, the dry processing using dense medium reduced the ash content of the feed coal from 45.23% to 37.60% for the −50+6 mm fraction, achieving a yield of 55.14%. The second/middling product from this fraction had an ash content of 54.61%. For the −25+6 mm fraction, the ash content of the feed coal was reduced from 48.90% to 40.07%, with a yield of 62.40%. The second/reject from this fraction had an ash content of 63.54%.

The results indicate that processing the finer size fraction (-25+6 mm) achieves a higher yield relative to the feed input and removes a significant amount of reject material with ash content greater than 60% compared to the coarser size fraction (-50+6 mm). This suggests that the finer size fraction (-25+6 mm) is more effective in separating coal from impurities, leading to better overall performance in terms of yield and quality of the clean coal product. Additionally, sink and float analysis was conducted on the float material collected during experiment using specific gravity ranges from 1.30 to 1.90 with 0.1 increments. This analysis provided partition values for the two fractions (-50+6 mm and −25+6 mm). The partition curves are presented on Fig. 24.

At lower relative densities up to 1.47, the misplacement effect is minimal for both −50+6 mm and −25+6 mm size fractions. However, misplacement increases significantly beyond a density of 1.47 for the −50+6 mm fraction compared to the −25+6 mm fraction. This difference is

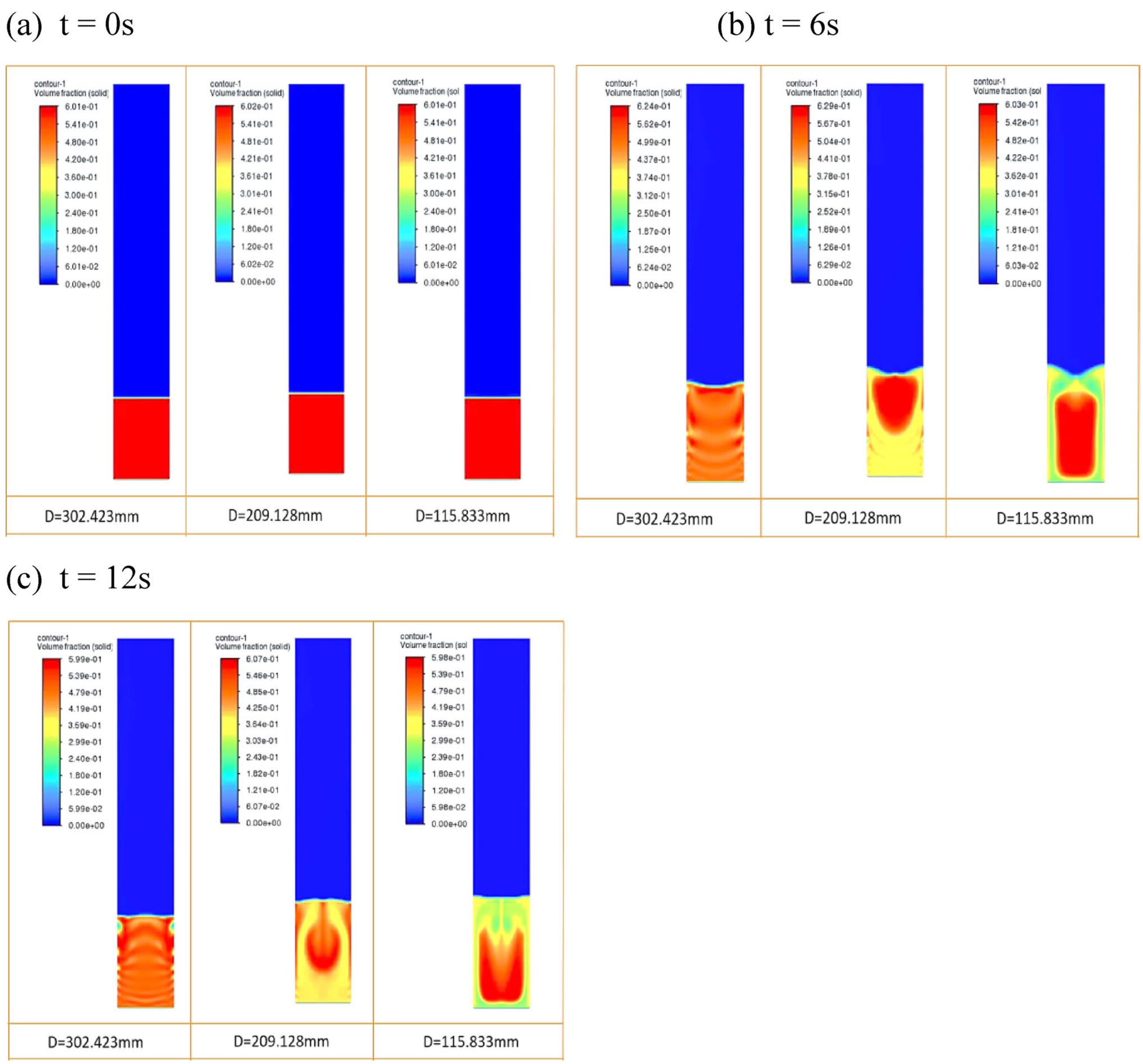


Fig. 23 Volume fractions of solids at different particle diameter at time (**a**) 0s (**b**) 6s (**c**)12s

Table 3 Different parameters used for dry process

Parameter used	Value
Coal feed size, mm	-50 + 6, -25 + 6
Feed quantity, kg	1.00
Nature of Coal	Coking
Initial bed height, cm	23
Expanded bed height, cm	29
Superficial Gas velocity, LPM	150
Medium size fraction, micron	-150 + 106
Medium density, g/cc	4.7
Initial bulk density, g/cc	2.65

attributed to the higher near-gravity material (NGM) content in the −50 + 6 mm fraction relative to the −25 + 6 mm fraction. The effective cut density is 1.68 for the −50 + 6 mm fraction and 1.78 for the −25 + 6 mm fraction. The probable error is 0.06 for the −50 + 6 mm fraction and 0.05 for the −25 + 6 mm fraction. Based on these results, the preconcentrate from the dry process of the size fraction −25 + 6 mm and the natural −6 mm fraction have been selected for further processing through flotation.

Table 4 Product balance of dry process (50–6 mm)

Feed Size: -50 mm	Products	Wt%	Ash%	Combustible Recovery (CR)	Organic Efficiency %
-50+6 mm (ADMFB)	**Pre-Concentrate**	**49.64**	**37.60**	58.30	91.86%
	Middling	40.38	54.61	34.50	
	Feed (total)	90.02	45.23	92.80	
-6 mm	**Natural**	**9.98**	**35.81**	7.20	
	Head(Calc.)	100.00	44.29	100	

Table 5 Product balance of dry process (25–6 mm) crushed

Feed Size: -25 mm	Products	Wt%	Ash%	Combustible Recovery (CR)	Organic Efficiency %
-25+6 mm (ADMFB)	**Pre-Concentrate**	**51.24**	**40.07**	61.94	89.26%
	Reject	30.87	63.54	22.71	
	Feed (total)	82.11	48.90	84.65	
-6 mm	**Natural**	**17.89**	**36.76**	15.35	
	Head(Calc.)	100.00	46.73	100	

Table 6 Partition values

Relative Density	-25+6 mm			-50+6 mm		
	Float, %	Sink, %	Partition Values	Float, %	Sink, %	Partition Values
1.35	0.09	0.00	1.00	0.36	0.00	1.00
1.45	4.73	0.16	0.97	34.98	1.16	0.97
1.55	18.62	1.72	0.92	23.32	4.05	0.85
1.65	52.55	9.56	0.85	34.13	17.94	0.66
1.75	19.00	9.87	0.66	5.65	33.68	0.14
1.85	1.13	7.84	0.13	0.72	17.59	0.04
1.95	3.88	70.85	0.05	0.84	25.58	0.03

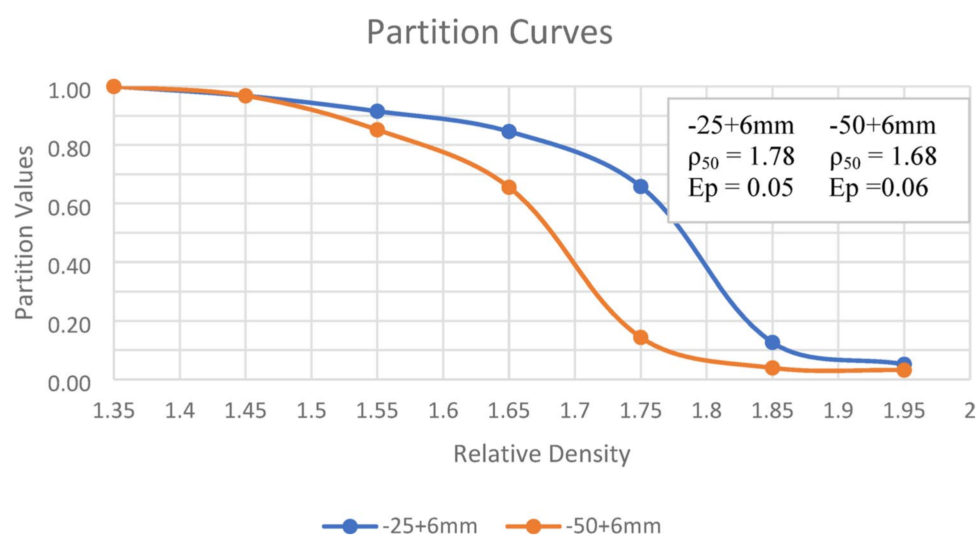


Fig. 24 Partition Curves

Flotation

The pre-concentrate (-25+6 mm) produced from ADMFB separator along with natural −6 mm fraction crush down to 0.5 mm for processing with froth flotation cell using different reagents. The reagents such as kerosene, diesel, NALCO reagent used as collectors and MIBC and NALCO reagent used as frother in the experimental study. In this study, the laboratory scale froth flotation cell has capacity two liter has been conducted the operation.

The prepared sample of below 500 microns taken for experimental study with an amount of 200 g in 2 L flotation beaker. The motor is switched on for mixing coal and water through rotor assembly. After mixing of pulp, the collector

Table 7 Different parameters used for froth flotation process

Parameter used	Value
Solid concentration, %	10
Pulp conditioning time, sec	120
Collector conditioning time, sec	120
Frother collection time, sec	120
Impeller speed, rpm	1300
Collector dosage, kg/t	Kerosene: 0.39, 0.77, 1.16, 1.54, 1.93 Synthetic: 0.42, 0.85, 1.27, 1.70, 2.12
Frother dosage, kg/t	MIBC: 0.09, 0.18, 0.26, 0.35, 0.44 Synthetic: 0.1, 0.2, 0.3, 0.4, 0,5

Table 8 Overall products of Ena OCP (Dry and flotation process)

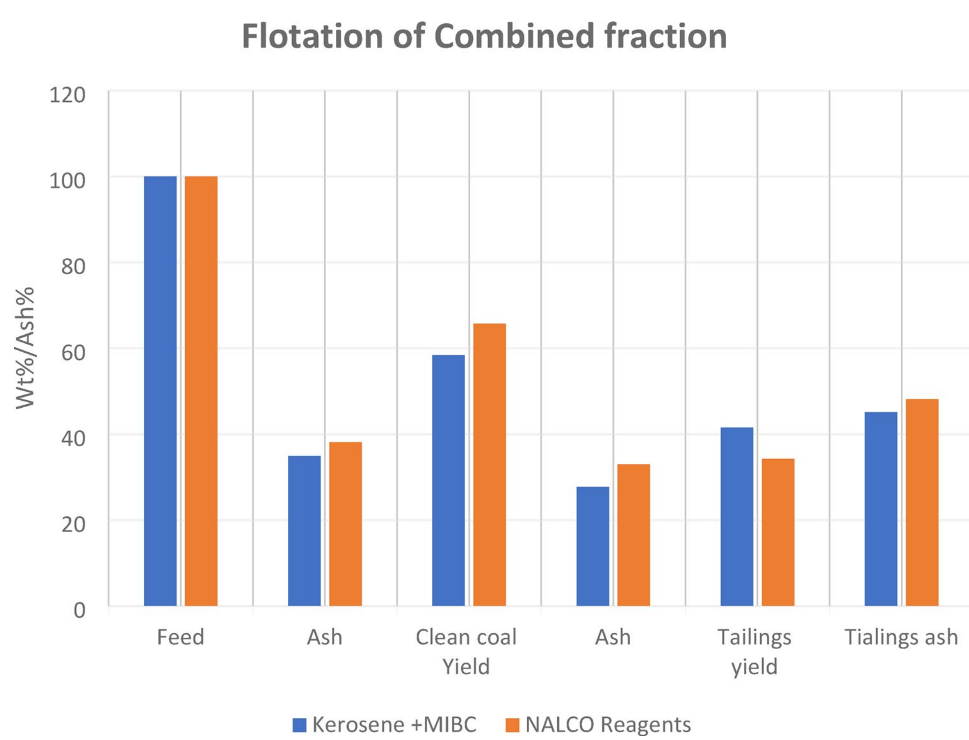
Product	Yield%	Ash%
Clean coal	45.42	32.94
Middling	23.71	48.20
Rejects	30.87	63.54
Feed (total)	**100.00**	**46.00**

is added to the pulp for conditioning for a fixed duration. After conditioning of collector, the frother is added to pulp for formation of froth. After few seconds, the air supply is switched on for creation of bubbles. The froth is collected from the top of the cell & that of tailing portion is collected in a beaker and allowed to settle for an hour recover the gangue portion through dewatering. The froth sample and tailing sample were dried in hot air over at 110 °C for 5–6 h for removal of moisture from sample. The dried samples were weighed and grind to 72 mesh for ash analysis. The reagents such as kerosene, NALCO synthetic is used as collectors and MIBC, NALCO synthetic is used as frothers. The parameters maintained during froth flotation experimental study is given at Table 7.

From Fig. 25, it was observed that using a combination of kerosene (0.77 kg/t) and MIBC (0.18 kg/t) reduced the feed ash levels from 34.96% to 27.72%, achieving a yield of 58.47% and with synthetic reagents, with 0.85 kg/t collector and 0.20 kg/t frother, reduced the feed ash from 38.17% to 32.94%, with a higher yield of 65.70%. The tailing ash content was 48.20% for synthetic reagents, which is higher than the 45.16% tailing ash for kerosene and MIBC. Overall, both reagents demonstrated the ability to reduce the feed ash by 6–7 units. However, the synthetic reagent proved to be more effective, yielding a higher recovery compared to the combination of kerosene and MIBC. The selection of reagents depends on their availability, cost and the desired product ash content for end use. The overall balance of products is provided in Table 8.

The overall balance (feed ash is 46%) of dry process and froth flotation process gives the clean coal yield of 45.42% with ash of 32.94% and middling yield of 23.71% with ash of 48.20%. The adequate enhancement ash degradation of the clean coal may be blended with high quality imported coal, that useful for steel making or metallurgical industries. The middling can be utilized for power generation in thermal power plants in India.

Fig. 25 Results of flotation tests



Conclusions

To efficiently utilize Indian high ash coking coals while addressing pressing water scarcity issues, a novel approach combining dry and froth flotation processes has been developed. This integrated methodology not only enhances the separation efficiency of valuable coal components but also significantly reduces water consumption during processing. Preliminary results are showed from above investigation and signified that this innovative technique could optimize resource utilization and sustainability in the coal industry, aligning with environmental and economic objectives. The parametric study identified optimal air flowrate, bed height, and medium particle size for controlling bed density and stability in the dry process. For −50+6 mm coking coal, dry de-shaling reduced ash from 45.23% to 37.60%, yielding 55.14%, while−25+6 mm coal saw ash reduced from 48.90% to 40.07%, yielding 62.40%. Misplacement occurred beyond a specific gravity of 1.47 for the −50+6 mm fraction, and the effective cut gravity was 1.68. Froth flotation of deshaled coal reduced ash from 34.96% to 27.72% using kerosene and MIBC, achieving a yield of 58.47%, while synthetic reagents lowered ash to 32.94% which can be used as a blendable coking coal with high quality imported coking coal for coke making, with a higher yield of 65.70%. Overall, combining dry and flotation processes lowered ash content from 46% to 33%, with a yield of 45.42%, producing middlings and rejects suitable for power generation.

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Author contributions Durga Prasad G: Manuscript writing, sample preparation, methodology, data analysis, CFD simulation. Sushanta K Behera: data analysis, manuscript review and editing, B C Meikap: Concept development, supervision, manuscript review and editing.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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