Study of importance of coal fines processing and applicability of different processing routes for improving process efficiency

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ABSTRACT

National Steel Policy 2017 envisages crude steel capacity to grow upto 300MTPA by 2030-31 and coal, being one of the major requirements, will play an important role in achieving the target. There are a few substitutes e.g. Biomass, Charcoal etc., which can be used in place of coal but none of them can replace coal entirely as of now. The reserves comprising of good quality coal are fast depleting. Hence, processing of low grade coal and effective usage of coal preparation plants (CPP) disposed tailings are of grave importance. Processing of coal fines are carried out by different beneficiation routes mainly froth flotation, autogenous cyclones etc. Liberation size is decreasing drastically and existing methods are inefficient to fully recover the fines.

Applicability of two processes - selective flocculation and liquid-solid fluidization - on processing of coal fines of Eastern India have been attempted in this work. Different coal samples and size fractions have been taken to test the feasibility of the said beneficiation routes. While liquid-solid fluidization gave better results at relatively coarser sizes, results were good at finer sizes in selective flocculation of coal fines. Effect of operational parameters on the combustible recovery of coal fines and the process efficiency have been investigated.

Keywords: Beneficiation routes, Liberation size, Coal Preparation Plants (CPP), Coal processing, Selective flocculation, Liquid-solid fluidization.

1. INTRODUCTION

Coal deposition in India has been stated as of 'Drift' origin, this being the one among varied reasons for the presence of inherent ash. Coal reserves in India account for only 0.9% of total coal reserve of the world because of non-uniform geographical distribution. Coal has been the world's fastest growing energy source in recent years – faster than gas, oil, nuclear, hydro and renewables (Parekh 2009). Coal has played this important role for centuries, not only providing electricity, but also an essential fuel for steel and cement production, and other industrial activities. Due to sudden hike in oil prices in the early 70's, coal became the dominant source of energy in the world, especially for countries like India where oil in desired quantity is not available (Luttrell, Honaker, and Phillips 1995; Tripathy et al. 2016). Hence, coal fines processing is of paramount importance and has been tried with two different routes in this work (Bhattacharya 2015; Kumar et al. 2018).

Selective flocculation has been attempted since a long time in mineral processing to address the problem of fines (Parazak et al. 1988; Somasundaran and Runkana 2000; Song and Lu n.d.). Higher molecular weight polymers have been used as flocculants for colloidal suspensions to separate and dewater solid-liquid (water) systems (Moudgil, Mathur, and Thatavarthy 1997; Pearse 2005; Quan and

Wang 2014). Adsorption of polymers on minerals and the rate involved are dependent on molecular weights, nature and concentration of functional groups and configuration, the mineral properties such as surface charges and oxidation state and solution properties such as ionic strength and solvent power for the polymer (FRIEND and KITCHENER 1973; Sabah and Cengiz 2004; Yang et al. 2019). In present study, polyacrylamide (PAM) has been used as flocculant and Sodium hexametaphosphate (SHMP) as dispersant for selective flocculation of coal fines.

Liquid-solid fluidization is the phenomenon of maintaining solid particles in suspension by applying an upward flow of liquid (Galvin, Walton, and Zhou 2009; Sahu et al. 2011; Tripathy et al. 2017). Fluidized bed separator is a type of gravity separators, where separation of the particles is caused because of the differential terminal velocities of the constituents of the feed. Because of wide variation of properties of ores, ore-specific fluidized bed separator is needed for the processing (Fan, Yamashita, and Jean 1987; Gernon and Gilbertson 2012; Tripathy et al. 2013). Fluidization experimental conditions are set according to physical properties of the coal particles. Properties of packed/fluidized beds are equally important for predicting bed behavior. Superficial fluid (water, in this case) velocity is crucial parameter for liquid-solid fluidization operation and minimum fluidization velocity is characteristic feature of fluidized beds as it marks the change of a packed bed to fluidized bed (Asif and Ibrahim 2002; Di Felice 1995; Ma and Zhao 2018; Rasul, Rudolph, and Wang 2000). Hydrodynamics and separation behavior of the liquid-solid fluidized bed separator have been analyzed in this work. In this work, the above described techniques have been used to wash different coal samples. Effects of different operating variables on combustible recovery%, ash rejection% and separation efficiency have been described.

2. SELECTIVE FLOCCULATION

2.1 MATERIAL

The run-of-mines coal sample was collected from Indian eastern coalfields. The sample was taken after rotary breaker and vibratory screen for -1 mm (1000 μm). Sample was subjected to sampling by riffling and coning-quartering. Representative samples were taken for size-wise proximate analysis and result is given in Table 1.

Table 1: Size-wise proximate analysis of coal sample

Components	+1000 μm	-1000+500 μm	-500+100 μm	-100 μm
Ash, %	33.25	32.57	31.96	31.58
Volatile Matter, %	33.71	33.12	33.81	34.02
Moisture, %	5.81	6.27	5.16	4.69
Fixed carbon, %	27.23	28.04	29.07	29.71

Sample was ground and sieved to obtain size fraction of -100 μm for selective flocculation studies. Commercial polyacrylamide-based flocculant (PAM) was procured from “HiMedia Laboratories Pvt. Ltd.”, Mumbai, India. Sodium hexametaphosphate (SHMP) was used as dispersant and Sodium hydroxide (NaOH) was used as pH modifier.

2.2 METHOD

The selective flocculation study was carried out in a 500 ml graduated measuring cylinder. Slurry was prepared by mixing water with coal particles of -100 μm size according to the required pulp densities (% w/w). Then required amount of dispersant, SHMP (expressed in terms of gpt), was added to the slurry. Proper pH was maintained by adding pH modifier NaOH. Then the cylinder containing slurry was provided a conditioning time of around 5 minutes at high shear rate. Required flocculant dose of PAM was added to the slurry (expressed in terms of gpt) and the whole mixture was then stirred at low shear rate. After allowing the slurry to settle for a definite period of time, supernatant liquid and flocculated sediment were collected separately. The concentrates obtained from tests were subjected to ash analysis. % combustible recovery and % ash rejection of the concentrates were calculated by using standard formulas and performance of the process was expressed in terms of separation efficiency.

2.3 RESULTS & DISCUSSIONS
2.3.1 PRELIMINARY TESTS

Some preliminary experiments were conducted to optimize the dispersant dose for the given coal and experimental conditions. For this purpose, tests were performed by varying dispersant dosage at constant pulp density of 10%, pH 9. Dispersant dosage was varied between 50 and 400 gpt. Result has been presented in Figure 1. Basic pH was maintained for flocculating coal particles. Previous researchers have found out that alkaline environment is favorable for enhanced formation of flocs and less entrapment of gangue particles in flocs.

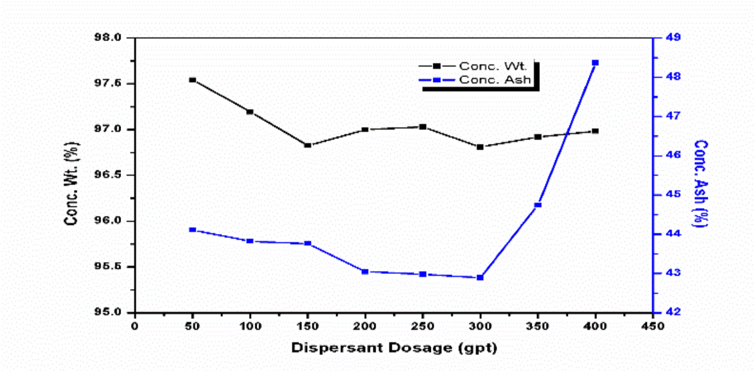

Figure 1: Effect of different dispersant dosage on flocculated concentrates

It can be seen from the graph that with varying dispersant dosage conc. wt.% and conc. ash% didn't follow a regular pattern. However, at dispersant dose of 300 gpt, conc. wt.% and conc. ash% was found to be minimum suggesting better dispersion of the particles and thus chosen for further tests.

2.3.2 SELECTIVE FLOCCULATION TESTS

Term 'Separation Efficiency' has been used to express the efficiency of the flocculants used for this process. Separation efficiency can be calculated by the formula:

$$\text{Separation Efficiency (SE, \%)} = Combustible\ recovery - Ash\ recovery$$

$$\text{Where, Combustible recovery\% in clean coal} = \frac{Y_c(100-A_c)}{(100-A_f)}$$

$$\text{Ash recovery\% in clean coal} = \frac{Y_c A_c}{A_f}$$

$$\text{Ash rejection\% in clean coal} = 100 - \frac{Y_c A_c}{A_f}$$

Plackett-Burman design of experiment has been chosen for studying the effects of input variables i.e. pulp density, flocculant dosage and pH on output parameters i.e. combustible recovery, ash rejection and separation efficiency. The design of experiment was based on three variables and two levels as discussed in Table 2, where actual and coded variables have been presented. The total runs were 12, as defined by Plackett-Burman design method.

Table 2: Ranges and levels of input variables in Plackett-Burman design

Variables	Coded symbol	Levels and range	
		-1	+1
Pulp density, % w/w	PD	5	10
Flocculant dosage, gpt	FD	50	100
pH	pH	9	11

2.3.2.1 EFFECT ON INPUT PARAMETERS ON ASH REJECTION:

Effect of pulp density, flocculant dosage and pH were studied on %ash rejection of flocculated sediment and has been shown in Figure 2. Dispersant dosage was kept constant i.e. 300 gpt for all tests.

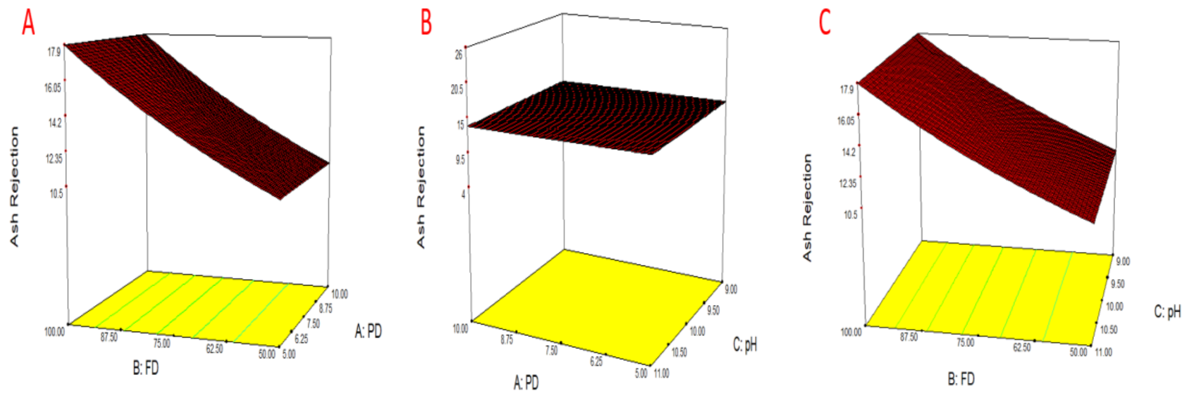

Figure 2: Ash rejection Vs. Inputs- A) PD & FD, B) PD & pH, C) FD & pH

It can be seen from the above graph that % ash rejection is significantly affected by interactional effect of pulp density and flocculant dosage, pulp density and flocculant dosage. In this case, pH doesn't have much effect on ash rejection. Increase in flocculant dosage, increases %ash rejection of the flocculated sediment.

2.3.2.2 EFFECT ON INPUT PARAMETERS ON COMBUSTIBLE RECOVERY

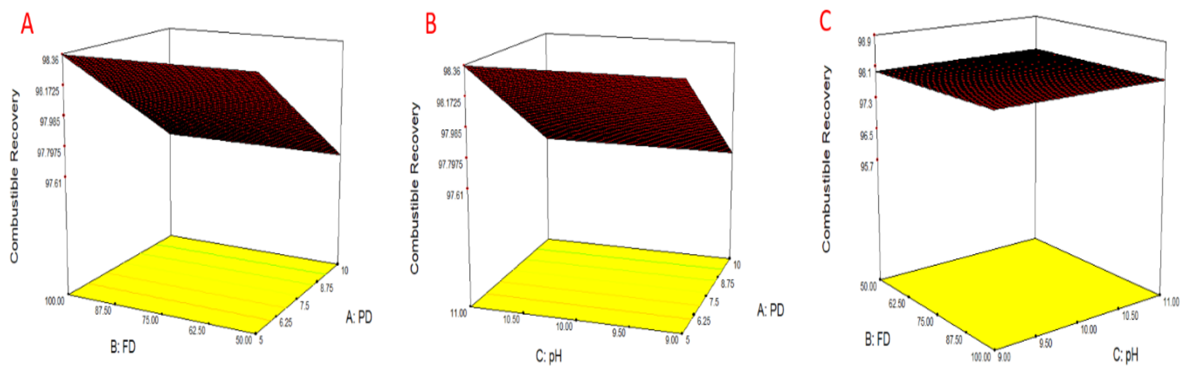

Figure 3: Combustible recovery Vs. Inputs- A) PD & FD, B) PD & pH, C) FD & pH

Effect of pulp density, flocculant dosage and pH were studied on %combustible recovery of flocculated sediment and has been shown in Figure 3. Dispersant dosage was kept constant i.e. 300 gpt for all tests. This is most affected by pulp density, flocculant dosage and interactional effect of pulp density and flocculant dosage.

2.3.2.3 EFFECT ON INPUT PARAMETERS ON SEPARATION EFFICIENCY:

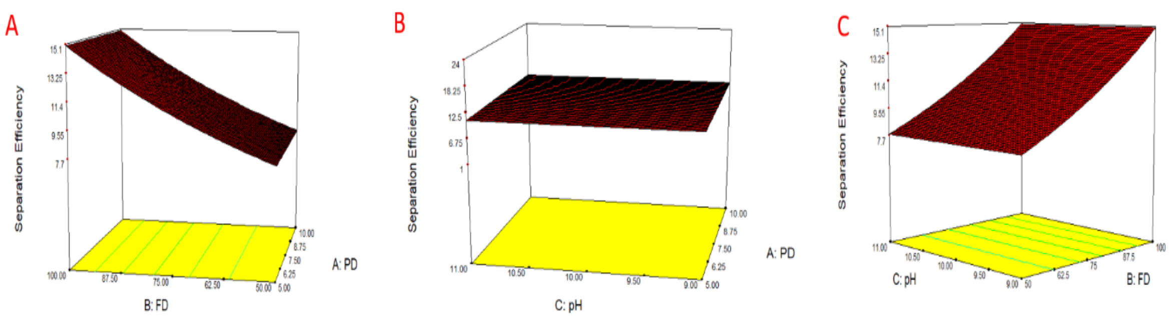

Figure 4: Separation efficiency Vs. Inputs- A) PD & FD, B) PD & pH, C) FD & pH

Effect of pulp density, flocculant dosage and pH were studied on separation efficiency of flocculated sediment and has been shown in Figure 4. Dispersant dosage was kept constant i.e. 300 gpt for all tests. Basic pH is favourable environment for flocculating coal particles. Optimum dosage of flocculant and dispersant is crucial for bringing out the desired results. It can be concluded by the results that selective flocculation can be opted for washing fine coal particles within certain range of input variables. Selectivity of the process can be achieved by maintaining alkaline environment and selecting proper dispersant and flocculant to introduce hydrophobic flocculation.

3. LIQUID-SOLID FLUIDIZATION

3.1 MATERIAL

Non-coking coal, of Indian eastern coalfields, has been used for this study. The sample was taken after rotary breaker and vibratory screen for -1 mm (1000 µm). Sample was subjected to sampling by riffling and coning-quartering. Representative samples were taken for size-wise proximate analysis and result is given in Table 3. This sample was crushed and size classified into six different size fractions: -1000+850 µm, -850+500 µm and -500+300 µm. Hydrodynamics studies of all the fractions were carried out and analyzed to study the fluidization behavior of the liquid-solid fluidized bed under different operating conditions.

Table 3: Size-wise proximate analysis of coal sample

Feed size, µm	Ash, %	VM, %	Moisture, %	FC, %
-1000+850	30.0248	28.2988	5.5203	36.1561
-850+500	29.4422	28.3746	6.2742	35.9090
-500+300	28.9749	28.2051	6.4175	36.4025

3.2 METHOD

Schematic description of the experimental set-up: It is a glass cylindrical column of 1.5 m height and 0.1 m diameter. Water was pumped through a rotameter in a controlled manner from the bottom of the fluidization column. U-tube mercury manometer is used to measure pressure drop across the fluidization column. The expanded bed height was measured manually. Different rotameters having different ranges i.e. 0-50 L/h, 50-500 L/h and 100-1000 L/h were used to measure water flow rates. There are five tapping points for collection of the samples at different tap heights in the fluidization column during the experiments. The different overflow tapping heights are at 12, 37, 62, 87 and 112 cm. Experiments were conducted at various feed sizes, overflow tap heights, bed heights and superficial velocities.

3.3 RESULTS & DISCUSSIONS

3.3.1 HYDRODYNAMICS STUDIES

For a given feed size, bed height and superficial fluid velocity, hydrodynamics studies determine how the sample will behave in the fluidization column. The minimum fluidization velocity required for the particles segregation has been observed and used to choose the range of superficial water velocity and design the experimental conditions. Figures. 5 to 7 show the pressure drop and expanded bed profile of different size fractions at different bed heights.

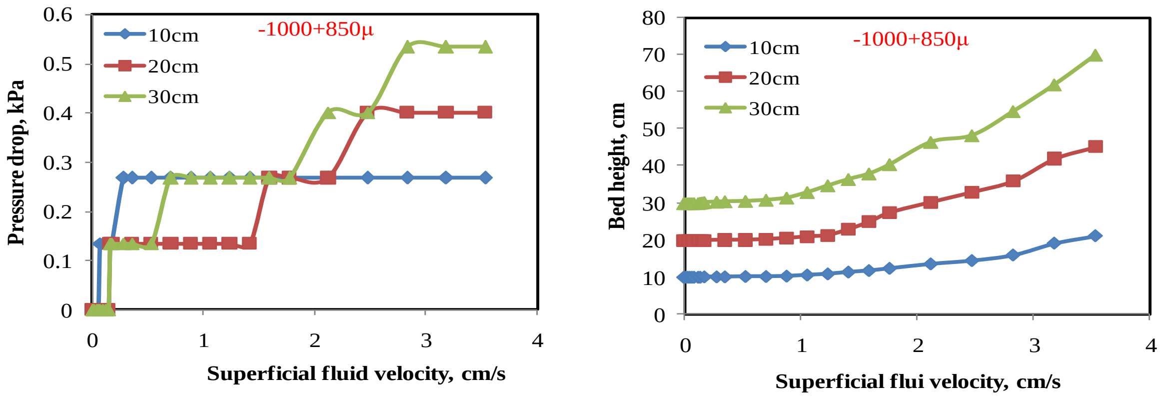

Figure. 5: Pressure drop (left) and bed expansions (right) of coal particles of size -1000+850 µm at bed heights 10, 20 and 30cm

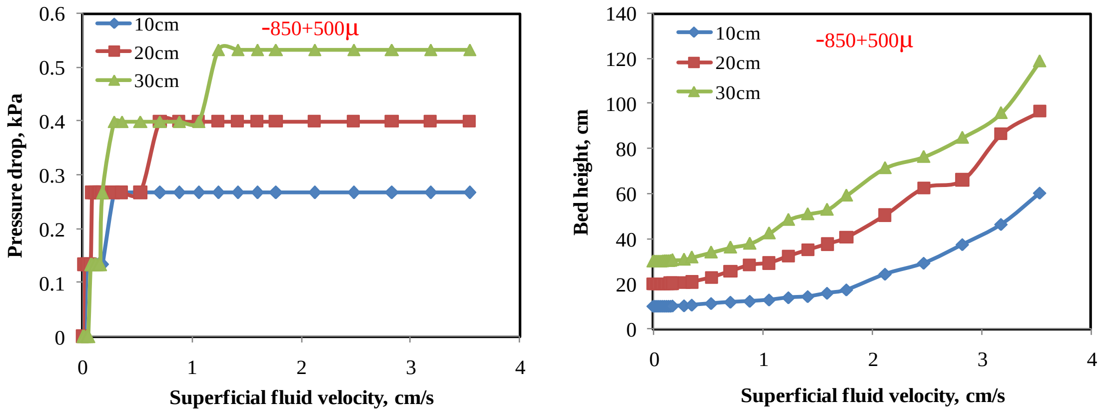

Figure. 6: Pressure drop (left) and bed expansions (right) of coal particles of size -850+500 µm at bed heights 10, 20 and 30cm

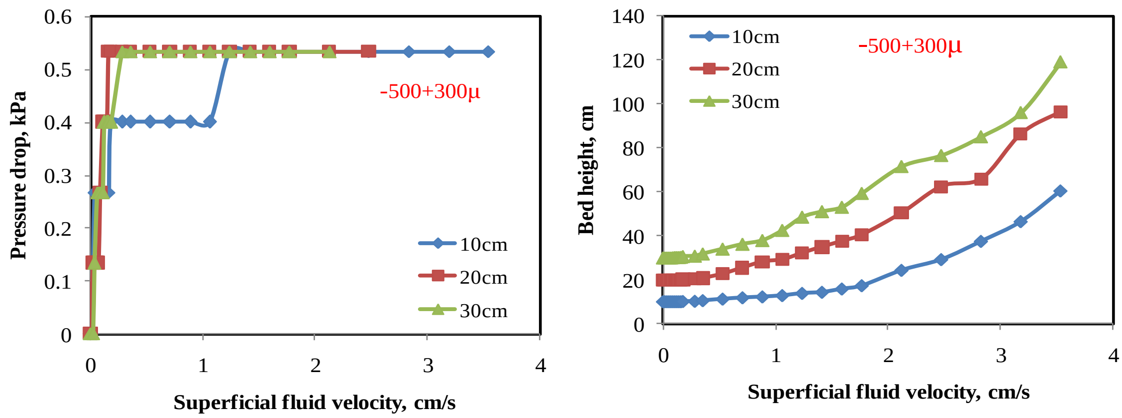

Figure. 7: Pressure drop (left) and bed expansions (right) of coal particles of size -500+300 µm at bed heights 10, 20 and 30cm

With increase in static bed height, pressure drop increases in case of all the size fractions. The total weight of the bed of particles increases with increase in static bed height, which would require higher force for particles to fluidize resulting in the increase in pressure drop. With increased particles size ranges, the slope of pressure drop decreases. A fixed bed, made of larger particles, has more bed permeability offering less resistance to the flow of water, resulting in lower pressure drop until the onset of fluidization. Once the particles are fluidized, the pressure drop in the bed is no longer affected by the particle size.

3.3.2 FLUIDIZATION STUDIES

Taguchi design of experiment was chosen to study the significance of operating variables. The design of experiment was based on four variables and three levels as discussed in Table 4, where actual and coded variables have been presented. The total runs were 9, as defined by Taguchi design method.

Table 4: Ranges and levels of input variables in Taguchi design

Variables	Levels and range		
	-1	0	+1
Feed size, µm	925	675	400
Superficial velocity, cm/s	1.06	1.41	1.77
Overflow tap height, cm	12	37	62
Bed height, cm	10	20	30

3.3.2.1 EFFECT OF INPUT PARAMETERS ON ASH REJECTION:

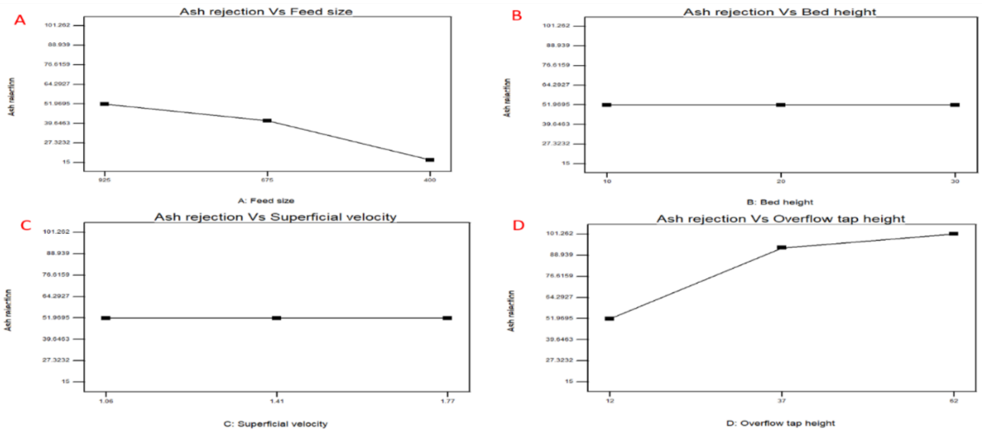

Figure 8: Ash rejection Vs Inputs- A) Feed size, B) Bed height, C) Superficial velocity & D) Overflow tap height

It can be seen from the above figure that with decrease in feed size, %ash rejection decreases. Bed height and superficial fluid velocity don't affect ash rejection significantly. With increasing overflow tap height, ash rejection increased. Overflow tap height is the most significant input parameter to affect ash rejection.

3.3.2.2 EFFECT OF INPUT PARAMETERS ON COMBUSTIBLE RECOVERY:

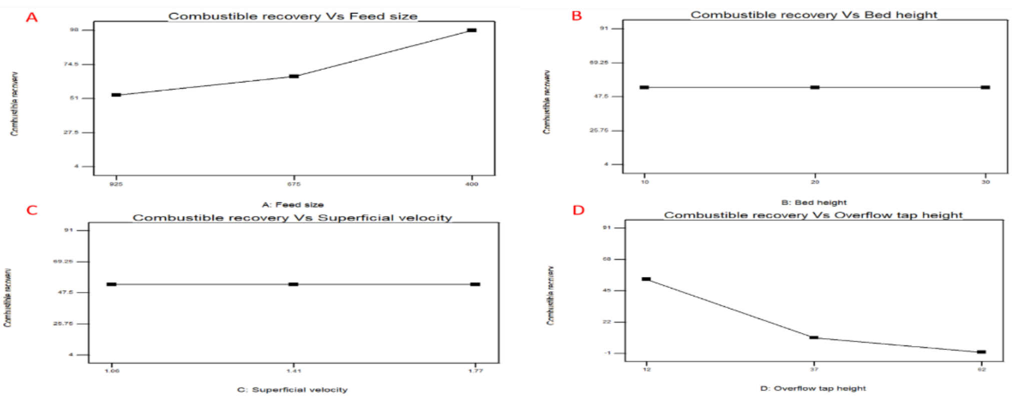

Figure 9: Combustible recovery Vs Inputs- A) Feed size, B) Bed height, C) Superficial velocity & D) Overflow tap height

From the above figure it can be observed that, overflow tap height affects %combustible recovery significantly. Concentrates obtained at higher overflow tapping heights have less combustible recovery. They don't show good carbonaceous matter recovery as suspended particles don't fluidize beyond a certain height at a given superficial velocity. Feed size is the second most significant input parameter to affect recovery of carbonaceous matter.

3.3.2.3 EFFECT OF INPUT PARAMETERS ON SEPARATION EFFICIENCY:

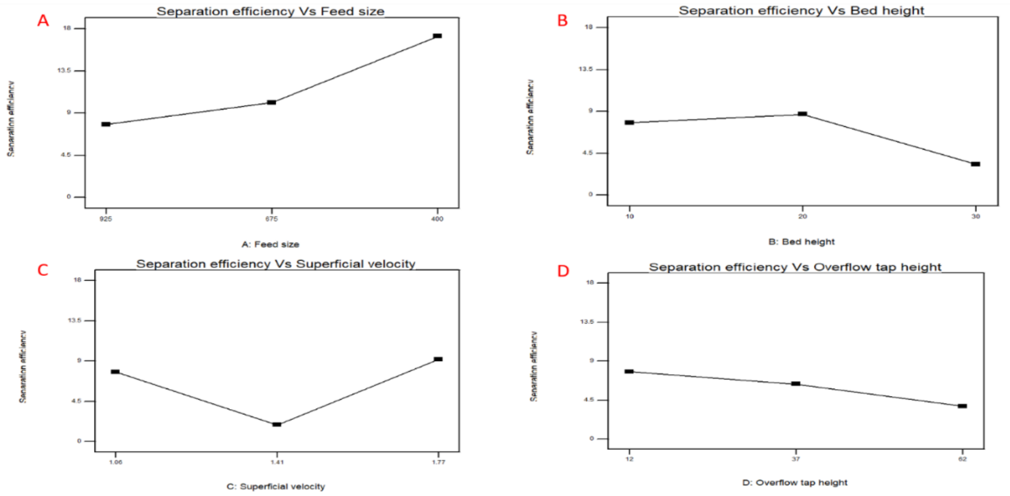

Figure 10: Separation efficiency Vs Inputs- A) Feed size, B) Bed height, C) Superficial velocity & D) Overflow tap height

Above figure shows the effects of input variables on separation efficiency of the process. Superficial velocity is the most significant parameter to affect the separation efficiency of the process. A certain superficial velocity is required to fluidize particles of certain size, density (weight) and shape. It was observed from the results that superficial water velocity affects the process efficiency more as compared to other operational parameters. Hence, it should be carefully chosen for better performance of the separator. Results were satisfactory for achieving certain ash rejection and thus can be suggested for coal cleaning.

4. CONCLUSIONS

ROM coal samples from eastern coalfields were tested for its amenability to beneficiation by different routes namely selective flocculation and liquid-solid fluidization. Different size-fractions were treated under various set of experimental conditions. From the obtained results, it was observed that by using liquid-solid fluidization, relatively coarser fraction i.e. upto 300/100 µm can be washed. A concentrate of 22.94% ash was obtained with separation efficiency of 17.18% from feed of 28.97 ash% under optimal experimental condition. Whereas, selective flocculation can be used to wash finer fractions i.e. -100 µm. under optimum set of experimental conditions, concentrate of 26.04% ash was obtained with separation efficiency of 23.19% from feed of 31.58% ash. Hence, both the techniques can be suggested for further experimentation.

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