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STUDY OF THE SEPARATION FEATURES OF FINE COAL CLEANING IN KELSEY CENTRIFUGAL JIG

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ABSTRACT

Kelsey Centrifugal Jig was found to be promising for the beneficiation of fine coal particles. The present study was aimed at in-depth understanding of the separation features of Kelsey Jig through detailed experimentation. Beneficiation of fine coal of size 150 x 300 µm was studied in a laboratory Kelsey Jig. The thickness of the ragging bed is found to be an extremely crucial parameter apart from the other process parameters such as rotational speed and pulsation frequency. A constant pulp density (25% solids) of the feed slurry was maintained in the study. The feed rate was also kept constant at 50 kg/hr dry solids. Silica sand of size -1.68+0.85 mm was used as ragging material to avoid the pegging of internal screen having an opening of 425 µm. The rotational speed was found to have significant effect on the depth of the ragging bed and its porosity, which influenced the separation performance considerably. Pulsation was identified as the key factor in stratifying the coal bed and defining the misplacement as well as ragging bed porosity, which influenced the mass yield and quality of the products. Beneficiation studies were carried out with rotational speed varying between 900-1000 rpm while pulsation frequency was kept within 850-925 rpm. In a single pass through the Kelsey Jig 7-8% (absolute) reduction in the ash content of the feed material was observed at more than 55% mass yield. High rotational speed, moderate pulsation, and low ragging bed depth favored good cleaning. A high bed depth was found to facilitate rejection of high ash materials. It was established that Kelsey Jig is effective in fine coal cleaning though a controlled operation is required in order to achieve superior performance.

Keywords: enhanced gravity separator, g-force, separation performance, ragging material, coal beneficiation

INTRODUCTION

Mechanized mining operation along with its multiple advantages brought drastic changes in the ROM coal quality such as increased percentage of coal fines and dirt. Surface property-based separation processes such as froth flotation and oil agglomeration have been traditionally recognized as the only methods for cleaning fine coal. These processes are very selective in rejecting well-liberated mineral matters. However, they are much less effective if the feed contains disproportionate amount of composite particles. Surface based separation processes are very intricate, needing close attention and careful operation. The conventional gravity-based separation techniques using spiral concentrator, water only cyclone or dense media cyclone have all been found to be inefficient for cleaning ultra fine particles in terms of selectivity and recovery.

The problems associated with the surface-based separation processes as well as conventional gravity processes may be overcome using the relatively new genre of enhanced gravity separators. A Falcon Concentrator is a spinning fluidized bed concentrator, which is a combination of sluice and continuous centrifuge. It enables the treatment of particles in the size range of 15-20 µm. The Knelson Concentrator is a compact centrifugal separator with an active fluidized bed to capture the heavy minerals. It can treat particles ranging in size from 10 µm to a maximum of 2 mm. The multi-gravity separator combines the centrifugal motion of an angled rotating drum with

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the oscillating motion of a shaking table to provide an enhanced gravity separation of the fine particles (Pradip, 2006). The Kelsey Centrifugal Jig (KCJ) works on the separation principles of a conventional jig employing a centrifugal force field. A much higher G-force (80-100 G) is obtained enabling the treatment of particles between 5 and 500 μm.

The major advantage of enhanced gravity separation is its ability to reject composite particles more efficiently than flotation. Among the enhanced gravity separators, the KCJ is very promising due to its higher production capacities and utilization of less plant area. An industrial unit can treat nearly 100 tons of coal fines per hour. The KCJ is successfully demonstrated for the concentration of tin, mineral sand, gold, platinum ores and iron ore slime. It has also been tested in Australia for the removal of ash from coal fines (Riley and Firth 1993). Yerriswamy *et al* (2003) have attempted to quantify the performance of the KCJ by regression model for the prediction of yield and ash content of the clean coal. Tucker (1995) has developed an empirical model for the KCJ, which describes the probability of transfer of the feed material to the concentrate stream. He considered the G-force, ragging characteristic, particle size and stroke length to be the major operating variables influencing the size/recovery curve. Luttrell *et al* (1995) described the basic working principle of commercially available enhanced gravity separators such as Falcon Concentrator, Kelsey Jig, Knelson Concentrator, and Mozley Multi Gravity Separator. A review of the advantages and limitations of each for fine coal processing was provided in this work. Richards and Jones (2004) discussed the latest developments on Kelsey Jig and its recent application areas including fine gold recovery from leach tailing, magnesium mineral removal from nickel sulphide concentrates and zircon recovery from plant tailing.

While reports of the application of the KCJ are plentiful, literature on the fundamentals of separation behavior are very limited. The impact of the operating variables and the reasons for such influence, the guidelines for selecting the ragging material, etc., are not available. The complex interaction of the various forces and the net effect of them are not clearly understood. In view of the above, a detailed experimental work was taken up in the present study along with some theoretical computations to have a better understanding of the separation process in the KCJ. Efforts were made to establish the appropriate operating regime and the particle size and thickness of the ragging bed. The effect of the spin frequency and pulsation rate on the separation and the reason for the same was investigated. An attempt was made to compute the force field, particle momentum, and understanding of the ragging bed porosity to explain the experimental observations on the separation behavior and enhance the phenomenological understanding.

RELEVANT PRINCIPLE OF OPERATION

The Kelsey centrifugal jig is a significant departure from the conventional jig albeit some basic similarities. It utilizes all the parameters of conventional jig as well as the additional feature to vary the apparent gravitational field. The ability to increase the apparent gravitational field enhances the recovery of fine particles by improving their settling characteristics. The operating principle is described briefly below.

The KCJ is fed down a fixed central pipe and the feed slurry is distributed at the bottom of the bowl, which flows upwards over the surface of a bed of ragging material supported by a cylindrical screen. The screen is spun coaxially with the rotor and pressurized water is introduced into a series of hutches behind the screen. Water is pulsated through the ragging bed, which helps in stratifying the feed as well as dilating the ragging bed. Particles with specific gravity greater than or equal to that of the bed of the ragging material pass through the ragging bed. The principles of differential acceleration hindered settling, and interstitial trickling hold. The differential acceleration rates are substantially enhanced by the higher apparent gravitational forces arising out of the rotation. The denser particles pass through the internal screen to concentrate hutches and then through spigots to a concentrate launder. The lighter particles are swept away by the rising flow and are discharged over a ragging retention ring into the tailing launder as shown in Figure 1.

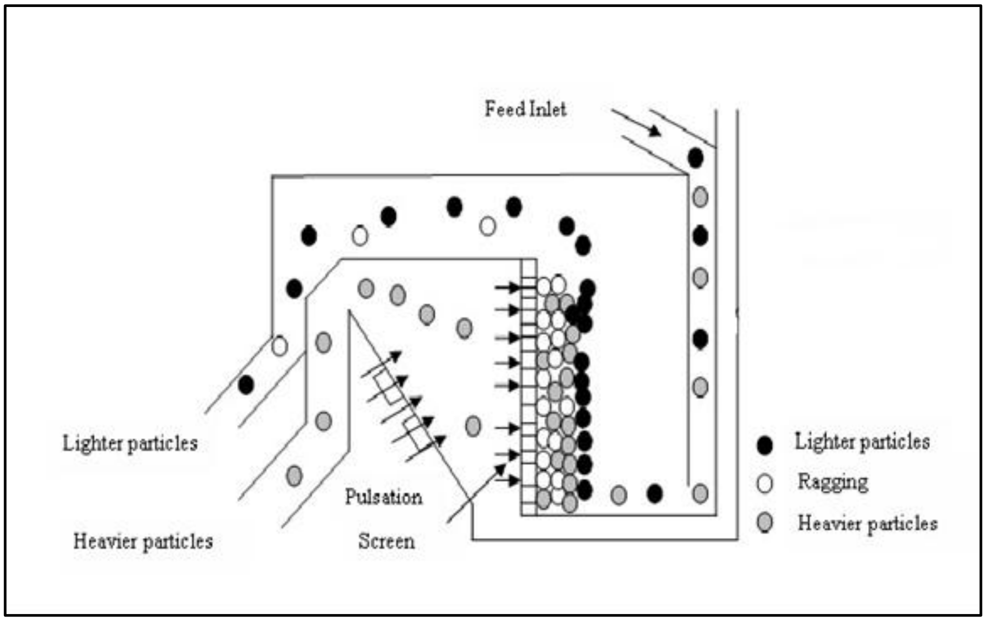

Figure 1. Partial cross-section of the Kelsey Centrifugal Jig

EXPERIMENTAL

A laboratory Kelsey Centrifugal Jig (Model No.J200 supplied by Roche Mining) was used in the present study. The separation efficiency of the KCJ depends upon several factors. These factors include the spin frequency, pulsation frequency, the nature of ragging material and the ragging bed thickness, the feed flow rate, hutch water addition as well as the screen opening. The complex interactions among these factors render the process extremely difficult to describe from a theoretical standpoint. An effort was made in the present work to understand the impact of some of these factors and the reasons for such impact. The influences of spin frequency, pulsation frequency and the depth of ragging bed were investigated. The other operating variables were kept constant during the experimental work. The feed rate was maintained at 50 kg/hr (dry solid basis). A screen with 425 micron opening was used and silica sand was used as the ragging material. The size of the silica sand was taken as 850 x 1680 micron. The hutch water flow rate was maintained at 25 L/min under all experimental conditions.

Materials

In order to avoid the effect of feed size on the separation efficiency, mono-sized coal particles were used in this study. The feed to the KCJ was screened at a size less than the internal screen size to avoid pegging. In the present study, coal particles of size 150 X 300 micron were used as feed material. The feed ash was estimated at 27.5% on dry moisture-free basis. The proximate analysis data of the feed coal are shown in Table 1. Silica sand with a specific gravity of 2.46 was identified as an appropriate ragging material. The particle size of the ragging material to be used depends on the pegging factor of the internal screen. Pegging factor is the ratio of internal screen aperture to the bottom size of the ragging material. It is recommended that for smooth operation pegging factor should be close to 0.6. Based on this, the minimum permissible size of the ragging material was estimated at 704 micron. Therefore, the minimum particle size of the ragging material used in this study was 850 micron. The top size of the ragging material was 1680 micron.

Table 1. Proximate analysis of the feed coal

Moisture (%)	Ash (%)	Volatile Matter (%)	Fixed Carbon (%)
2.52	27.5	30.2	42.3

Methods

Silica sand of size 850 X 1680 micron was fed through a central pipe first and was distributed over the cylindrical screen by the rotation of the bowl. Feed pulp having 25% dry solids (coal) by weight was fed through the central pipe. Hutch water was pulsated at a pressure of 500 kPa to stratify the feed material. Once the steady state was achieved, the heavier and lighter products were collected through tailing and concentrate launders, respectively. Subsequently, these are dried, weighed, and analyzed for ash. A set of experiments were carried out to study the effect of spin rpm, pulsation rate, and ragging bed depth on the separation performance. The ragging bed formation was established first by introducing the silica sand and noting the time after which no sand particles came out. Once the bed was formed, the coal slurry was introduced at the desired rate through a peristaltic pump. The levels of the process variables were set and the system was allowed to run for 15-20 minutes to achieve steady state. The samples were then collected and processed to generate the performance data. The results of these experiments in terms of product yield and grade are shown in Table 2.

Table 2. Experimental results under various operating conditions

	Experimental Conditions						
Test No.	**Bowl speed (rpm)**	**Pulsation (rpm)**	**Ragging weight (g)**	**Feed rate (kg/hr)**	**Product**	**Yield (%)**	**Ash (%)**
1	950	925	300	50	Conc.	83.4	22.4
					Tail	16.6	47.6
2	1000	900	300	50	Conc.	83.1	22.6
					Tail	16.9	48.5
3	950	900	275	50	Conc.	71.3	21.5
					Tail	28.7	39.1
4	900	925	275	50	Conc.	63.0	22.1
					Tail	37.0	37.0
5	1000	875	275	50	Conc.	63.9	23.5
					Tail	36.1	35.2
6	900	875	275	50	Conc.	53.1	22.5
					Tail	46.9	33.9
7	1000	900	250	50	Conc.	60.2	20.4
					Tail	39.8	35.8
8	950	875	250	50	Conc.	55.4	21.2
					Tail	44.6	34.9
9	900	900	250	50	Conc.	51.5	22.1
					Tail	48.5	31.9

RESULT & DISCUSSION

The clean coal ash data obtained in these experiments were in the range 20.4 - 23.5%. It may be noted that the feed coal contained 27.5% ash. Thus, reduction of ash was significant. However, more significant variation in the mass yield of the clean coal (51.5 - 83.4%) under the test conditions was observed. Large variation in the tailings grade (31.9 – 48.5% ash) was also observed. The results clearly indicate that by changing the operating conditions it would be possible to achieve either a purer concentrate or a rejectable tailing stream from the feed coal. There is also ample scope to manipulate the clean coal yield.

It is evident from Table 2 that when a larger bed depth of the ragging material (ragging material weight 300 g) is used most of the material report to the overflow. Only around 17% of the material is able to penetrate the ragging bed. This material is very heavy and a very high tailing ash (~48%) is obtained under these conditions. This is a significant finding; as such a step would effectively reject the high-ash bearing material from the feed before cleaning operations are taken up. Ragging bed depth must be kept low in order to obtain a low ash in the clean coal. A moderate pulsation is observed to produce better results in terms of the clean coal ash level. A high rotational speed appears to be better suited for achieving a lower ash in the clean coal while enhancing the mass yield of the clean coal product.

When considered from a fundamental standpoint the impacts of all these process variables individually on the separation features are indeed quite complex. In addition, these variables exhibit inter-dependence in determining the performance of the KCJ. This makes it further difficult to describe the effects of these variables in isolation. An attempt to describe the individual and the combined effects of these variables and the possible reasons for the same is made here in the light of the experimental observations.

Effect of ragging bed depth

The bed depth was varied by changing the total weight of the ragging material. The effect of ragging bed depth can be seen by comparing the results of Expt. No. 2 and 7. As the bed depth increased the yield to overflow (clean coal) increased substantially from ~60% to ~83%. The clean coal ash level also went up from 20.4% to over 22%. However, the more interesting observation was the increase in tailing ash which went up from ~35% to ~48% with the increase in the depth of the ragging bed. This is a significant observation as it provides guideline to use KCJ for different purpose, e.g. roughing or cleaning.

Figure 2 helps in understanding the effect of ragging bed depth. The ragging bed essentially acts as an obstruction to the movement of the particles through the screen. The greater the thickness of this obstruction the sluggish is the movement of the particles. The heavy particles in the stratified coal bed adjacent to the ragging bed take longer to be discharged at the other end of the screen. This is shown in Figure 2 where t_{f2} is greater than t_{f1}. As a result, the overall mass transport through the ragging bed decreases leading to accumulation of stratified coal particles close to the ragging bed. Due to the continuous inflow of feed pulp, the stratified heavier particles are more likely to be flushed away into the overflow stream since the chances of their penetration of the thick ragging bed are slim. This phenomenon is reflected in the results of the above two experiments. At a lower ragging bed depth, the clean coal (overflow) yield is lower (~60%) while a high clean coal yield (~83%) is obtained at higher ragging bed depth. As discussed, the chances of heavier particles reporting to the overflow are higher when the ragging bed depth is higher. This is also reflected in the low clean coal ash (20.4%) in the case of lower ragging bed depth and a high clean coal ash (22.6%) for higher ragging bed depth. At a high bed depth, only the heaviest particles are able to penetrate the ragging bed and the tailing ash, consequently, is very high. As the bed depth reduces, more material of relatively lower density also passes through the bed resulting in lower tailing ash level.

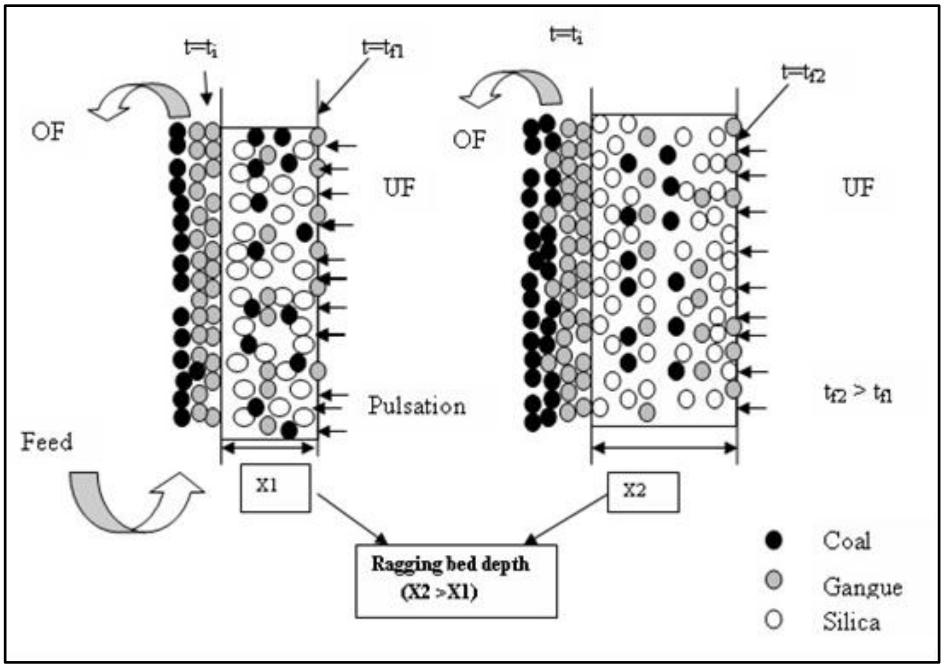

Figure 2. Schematic of separation features for different depths of the ragging bed.

Effect of Spin frequency

Spin frequency of the KCJ is essentially the rotational speed of the bowl. It defines the centrifugal field (G-force) operating on the system and the entire flow phenomena. It has significant effect on the nature of the ragging bed formed as well as the momentum of the solid particles. Increasing the spin frequency enhances the apparent gravitational field at the ragging bed surface as shown in Figure 3. A higher G-force increases the compactness of the ragging bed and reduces its porosity. A more compact bed prevents smooth passage of the particles through the bed and the screen. This is likely to lead to less material penetrating the ragging bed and result in a higher clean coal yield. In addition, only heavier particles are likely to be able to penetrate the ragging bed leading to a higher ash in the tailings stream. On the other hand, increasing the spin frequency increases the centrifugal force acting on the particles leading to a higher momentum of these particles. This is likely to enhance the probability of passage of more particles through the bed leading to a lower clean coal yield and a lower ash of the reject stream.

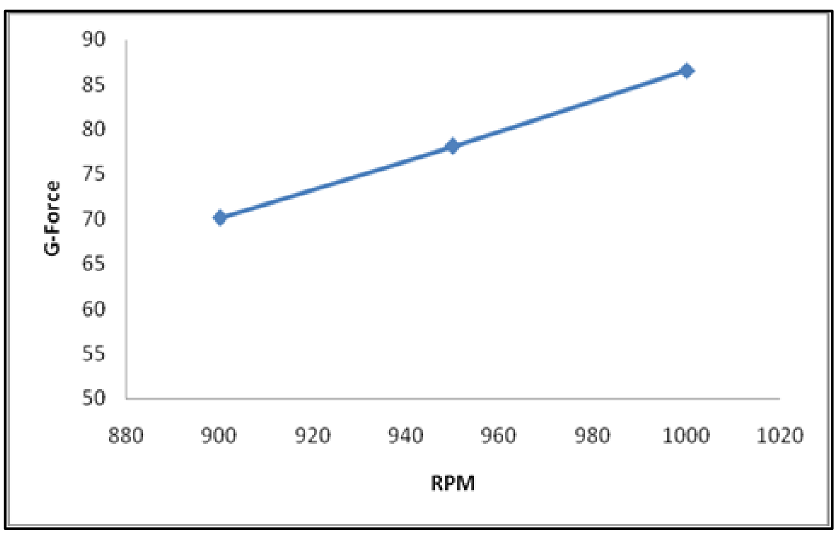

Figure 3. Variation of G-force with spin frequency.

The particle momentum evidently plays an important role. It is certainly necessary to get an idea of the momentum of the particles and an effort in this regard is presented here. The passage of the particles through the screen can be described by considering the various forces acting on the particle in centrifugal sedimentation, which determines the settling characteristic of the particles (Wills and Napier-Munn 2006). Accuracy of the estimated terminal settling velocity from the force balance equation is strongly dependent upon accurate prediction of drag co-efficient, which is greatly affected by the settling regime. Hartman *et al* (1989) proposed an empirical approach for the estimation of terminal velocity under gravity sedimentation, which is independent of settling regime (Stokesian or Newtonian). Extending this approach to centrifugal sedimentation the terminal velocity values were computed. The set of equation proposed by him is given below:

$$Ar = \frac{{d_p}^3 \omega^2 r \rho_f (\rho_s - \rho_f)}{\mu_f^2} \tag{1}$$

$$A = \log_{10} Ar \tag{2}$$

$$R(A) = 0.99947 + 0.01853 \sin(1.848A - 3.14) \tag{3}$$

$$P(A) = \left[(0.0017795A - 0.0573)A + 1.0315\right]A - 1.26222 \tag{4}$$

$$\log_{10} \mathrm{Re}_t = P(A) + \log_{10} R(A) \tag{5}$$

$$\mathrm{Re}_t = \frac{U_t d_p \rho_f}{\mu_f} \tag{6}$$

Where, d_p is mean equivalent spherical diameter, ω is angular velocity, ρ_s is density of particle, ρ_f is the density of fluid, μ_f is viscosity of fluid, Ar is Archimedes Number, U_t terminal velocity of particle, Re_t is the terminal Reynolds number.

In this approach the Reynolds number is estimated first to compute the terminal velocity. At terminal settling velocity, the momentum of the particle is then estimated as:

$$m_p U_t = \frac{\pi {d_p}^2 \rho_p \mathrm{Re}_t \, \mu_f}{\rho_f} \tag{7}$$

Using Eq. (1) to Eq. (7), the momentum of the particles with different density was estimated at different spin frequency. The variation in the momentum with spin frequency is shown in Figure 4. It shows that rotational speed has more prominent effect on the momentum of heavier particles (gangue mineral) as compared to that on the lighter particles (combustibles).

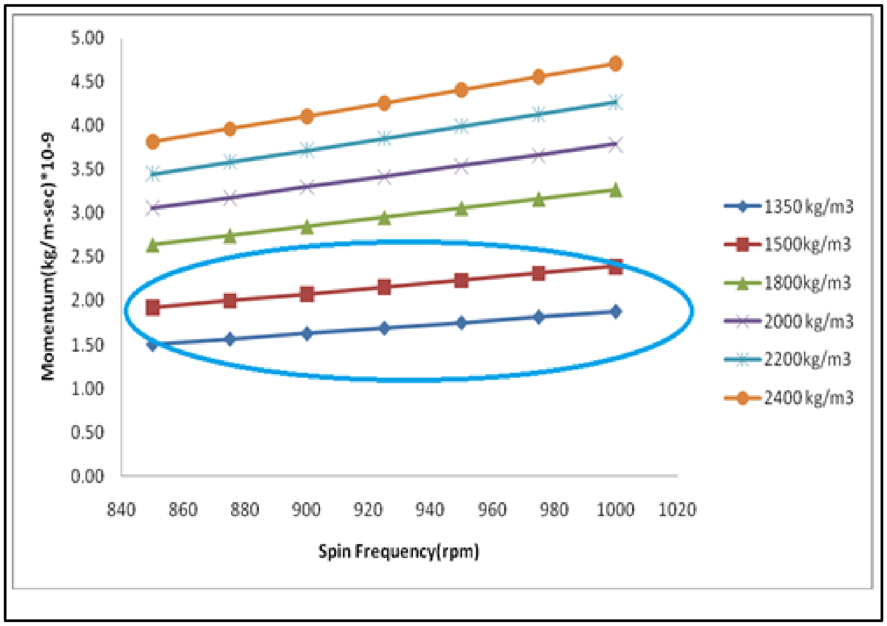

Figure 4. Changes in the momentum of a particle with spin frequency.

In the stratified particle bed, the particles with highest density values remain close to the ragging bed and hence, are likely to report to the tailing stream under most conditions. The lightest particles remain farthest from the ragging bed and hence, are unlikely to find a passage through the screen into the tailing stream. The particles with intermediate density values are the ones, which determine the grade and the mass yield of the products as the conditions are varied. If the momentum of these particles were sufficiently high to penetrate the ragging bed, they would pass through the screen and reduce the ash content of the tailing stream. Consequently, the yield of the clean coal would drop.

Thus, the effect of spin frequency is reflected in two contrasting phenomena, which nullify each other to a significant extent. The combined effect of these phenomena can be seen in the results of Expt. Nos. 7 and 9. Lower bed porosity and higher momentum of the particles at higher spin frequency result in higher yield of the clean coal and higher tailing ash. Expt. Nos. 5 and 6 also corroborate this. In view of the above, bed porosity appears to be playing a more dominant role. However, the clean coal ash also depends on the pulsation frequency, which has a strong influence on the porosity of the ragging bed.

Effect of pulsation

Pulsation mechanism creates a shock wave, which also has multiple effects on the separation process. Firstly, it dilates the ragging bed, which allows the particles to enter the bed. However, too high frequency does not allow effective enhancement of bed porosity due to too very little time for the dilation-contraction cycle of the bed. Therefore, the motion of the particles through the ragging bed becomes sluggish. This results in less material penetrating the ragging bed and the high clean coal yield at a high pulsation frequency is a testimony to that. Secondly, pulsation prevents the particles to reach their terminal velocity and maintain a differential acceleration between high and low density particles. The effect of shock waves is greater on the lighter particles than on the gangue material (heavier particles). Therefore, a higher pulsation frequency leads to less misplacement of lighter particles in the tailing stream. On the other hand, the transportation of relatively lighter ash-forming material into the clean coal stream is facilitated under this condition. This is reflected in the high tailing ash and a high clean coal yield at a high pulsation rate.

Comparison of the data for Expt. Nos. 4 and 6 reveal that relatively lower density material are prevented from being misplaced into the tailing stream at higher pulsation rate resulting in higher tailing ash. Consequently, the yield to the overflow stream also increases from 53% at lower pulsation rate to 63% at higher pulsation rate. Not much variation in the clean coal ash is observed which remained higher than 22%. Of course, the clean coal ash is also dependent upon the other parameters. In view of these observations and closer examination of other data in Table 2, it may be concluded that a moderate pulsation frequency should be used for better overall cleaning performance.

CONCLUSION

Kelsey centrifugal jig is established as a promising advanced gravity separator for fine coal cleaning. The ash content of the raw coal used in this study can be brought down by an absolute 7% in the clean coal in one single pass through the KCJ. There is immense scope for achieving a high clean coal yield while maintaining a relatively low clean coal ash level by controlling the process variables. The conditions have been identified under which the KCJ can be used as a roughing unit or a cleaning unit. Effective rejection of ash-forming material under a high ragging bed depth condition was accomplished. A low ash clean coal is achieved under high rotational speed and moderate pulsation frequency while keeping a small ragging bed depth.

The depth of the ragging bed is very crucial, as any change in the depth of the bed leads to drastic changes in the clean coal yield and the grade of the products. The spin frequency determines the centrifugal field and is primarily responsible for defining the entire flow pattern inside the bowl. The porosity of the ragging bed as well as the momentum of the particles is greatly affected by the spin frequency. It is established in the present work how the spin frequency needs to be controlled in order to achieve the target mass yield and grade of the products. The pulsation also has been shown to have significant influence on the porosity of the ragging bed as well as the differential acceleration of the particles. A high clean coal yield can be achieved through a high pulsation frequency. However, in order to achieve a low clean coal ash a moderate level of pulsation is recommended.

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REFERENCES

Holdich, RG, 2002. Fundamental of particle Technology, pp-77(Midland Information Technology and Publishing, UK).

Hartman,M, Havlin,V, Trnka,O, Carsky,M, 1989.Predicting the free fall velocities of spheres, Chemical engineering Science 44(8), pp.1743- 1745.

Luttrell, GH, Honaker RQ, and Philips, DI, 1995. Enhanced gravity separators: new alternatives for fine coal cleaning, 12th Int. Coal Prep. Conf., Lexington, KY, pp. 281–292.

Pradip, 2006. Processing of alumina-rich Indian iron ore slimes, International Journal of Mineral, Metals and Materials Engineering, 59(5), pp-551-568.

Riley, DM and Firth, BA, 1993. Application of Enhanced Gravity Separator for cleaning of fine coal, Proceedings Coal Preparation.

Richards, RG and Jones, TA, 2004. Kelsey Centrifugal Jig-An Update on Technology and Application, SME annual meeting.

Tucker, P, 1995. Modeling the Kelsey centrifugal Jig, Mineral Engineering, Vol.8, No.3, pp- 333-336.

Wills, B. A., Napier-Munn, T. 2006. Mineral Processing Technology, Elsevier Science & Technology Books,

pp 204.

Yerriswamy, P, Majumdar, A K, Barnwal, J, P, Govindarajan, B and Rao, T C, 2003. Study on Kelsey jig treating Indian coal fines, Mineral Processing and Extractive Metallurgy, Vol. 112, C1-C5.