Recent developments in beneficiation of fine and ultra-fine coal -Review paper

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Abstract

Generation of fines and ultra-fine is concept that mining and metallurgical sector can never shy away from since exploration coal commodity began. These coal fines and ultra-fines are what coal mines regard(ed) as waste material without economic value until present moment. Poor technologies in the past lead to stockpiling of large quantity of fines and ultra-fines and again increase in mechanization in mining has led to the generation what is considered as waste in large quantities making it thus difficult to treat the coal. This paper reviews recent developments in minerals processing beneficiation technologies of coal fines and coal ultra-fines

Keywords: Coal fines, Ultra-fine coal, Beneficiation, gravity concentration, coal flotation

1. Introduction

Coal has historically been a major contributor to economic growth and a key source of energy. However, the natural friability, mechanized mining, handling system and size reduction method to achieve a desired top size has led to increase in production of coal fines -1mm(Hacifazlioglu, 2012). Statistics show that over 30 billion metric tons of coal are available in the top 10 coal producing countries and owing to great difficulty in treating coal fines(CoalTech, 2016), they are thereof disposed and left on stock pile, slurry ponds and near mining sites since or added in steam coal regardless of fact that fines constitute of potential source of high energy coal(Department of Minerals and Energy, 2001; Oruç et al., 2010; Reddick et al., 2008).

Paths of utilizing illustrated in the Figure 1 below with respect to size and this residual energy source are being sightseen with increasing commitment because of increased cost of extraction due to rising energy prices, increased environmental concern regarding (spontaneous combustion, Acid mine drainage, dust release carbon-dioxide emissions and Sulphur-dioxide emission), diminishing vacant land for coal mine waste, depletion of higher-grade thermal coal and difficulty to access(Department of Minerals and Energy, 2001). These paths that explored are aimed at recognizing both the economic potential and the environmental risk posed by the discards because with huge amount of disposed coal fines there is potential to add back millions of metric tons into the market every year(ESI AFRICA, 2016). The areas to be explored in this study are enhanced gravity separation, oil agglomeration, flotation and gravity separation.

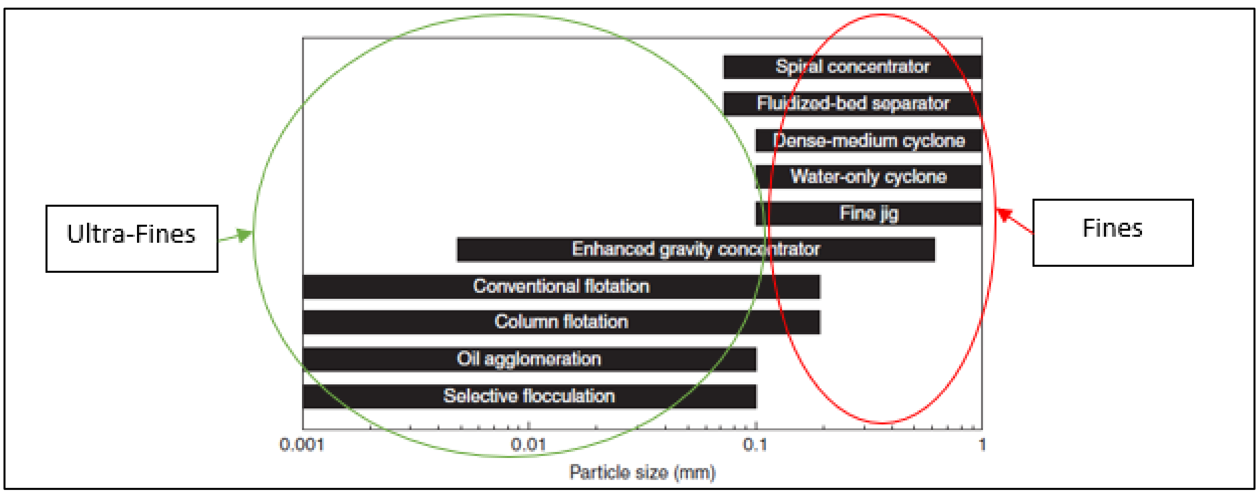

Figure 1: Treatment options for fines and ultra-fines, Source,(Erasmus et al., 2016; Osborne, 2013)

2. Methodology

The goal of this writing was to investigate distributed literature on the beneficiation of coal fines and ultra-fines in minerals processing sector to perceive the developments to date. Database such as Research gate, Elsevier and Informa PLC was utilized to acquire the data of the reviewed concept. This writing study was finished by looking in articles on the treatment of coal fines and ultra-fines and this extents from years 2015-2019. 58% of reference ranges from

2015-2019 and the rest from 2014 going backwards. Data from 2014 backwards was utilized as reference point from where everything began and where it is now.

3. Developments in processing fine and ultra-fine coal

3.1 Enhanced gravity separation

Enhanced gravity separator (EGS) has been commercially useful in industry and is cable of treating coal that was regarded as too fine to treat for water-based gravity separators. Such devices that where developed in minerals processing application include, Knelson concentrators, Mozley Multigravity separator and falcon concentrator(Luttrell et al., 1995). In their application on coal, such technologies can treat coal of 53μm and finer because of good preference i.e. relatively low cost and ease of handling. Due to factors such as a decrease in mass of particle, increased specific area and increased surface energy per surface area, coal becomes very difficult to treat using conventional gravity separation methods that were applied on fines because of weak gravity effect on ultra-fine particles. However, to overcome this challenge, enhanced acceleration is used to separate the clean coal fine coal from the gangue.

3.1.1 Mozley Multi-Gravity Separator (MGS)

Designed to treat material size below 500-1μm through density-based separation is a continuous thin film separator designed by M/s Richard Mozley limited from British technology group. This equipment combines other operational variables from other gravity based methods thus allowing effective separation of finer material or material with near specific density (Göktepe, 2005). The operating principle of the MGS can be visualized to a shaking table that is rolled into a drum, allowing it to rotate generating gravitational pull that is exerted on mineral particles as they flow in leveled water layer across the surface. Two version are available which are smaller laboratory unit illustrated in Fig 2. The important variables that govern the operation of the MGS are: speed of the drum, shaking intensity, wash water flow rate, tilt angle, feed rate and % solid as known as pulp density(Chan et al., 1991; Chaurasia and Nikkam, 2017).

The MGS comprise of two open-finished drums that are mounted consecutive. The drum pivots at speed variable somewhere in the range of 90 and 150 rpm, permitting force generation of somewhere in the range of 5 and 15 G to be produced at the drum surface(Wills and Finch, 2016). A sinusoidal shake with an amplitude of variable somewhere in the range of 4 and 6 cps is superimposed on the movement of the drum, the shake granted to one drum being adjusted by the shake bestowed on the other, in this way adjusting the whole machine. A scrapper mounted inside each drum on a different concentric shaft, driven somewhat quicker than the drum a similar way. This scrape solids settled up the incline of the drum, during the time they are exposed to counter current washing before being released as aggregate at the open, external, thin part of the bargain. The lower density minerals, alongside most of the wash water, stream downstream to be released through spaces at the inward part of the drum. In the case of cleaning coal, the high-density material that settle on the slope of the drum is regarded as gangue and the lower density material is regarded as clean coal.

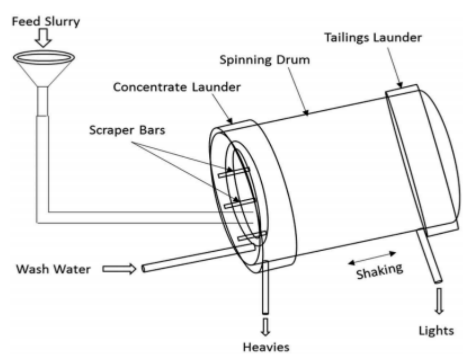

Figure 2: Illustration of multi-Gravity separator(Das and Sarkar, 2018)

An accord of adjustment on operational variables (Shake frequency, solid ratio, wash water, drum speed, shake amplitude and inclination/tilt angle) results in high concentration performance of Multi-gravity separator. Those operational parameters were evaluated and the results on Table 1 show the findings. This finding tends to show a similar trend on which levels of operation should parameter be at to be able to obtain maximum performance of MGS. Preliminary studies show that no separation takes place at speeds of less than 225 rpm, and the was water needs to be minimal normally kept constant at 1L/min to obtain better separation efficiencies.

Oluklulu & Koca(2018) evaluated the interaction between the parameters of MGS on the ash content and combustible recovery. The assessed operation parameters were shake frequency, solid ratio, drum speed and shake amplitude to assess of their important role in combustible recovery and % ash content . The optimum conditions obtained i.e. maximum combustible recovery and minimal ash content, were ascribed to lowest levels of solids and highest level of shake amplitude, shake frequency and drum speed. From the models generated from the experimental data showed over 95% of R^2 values depict that there is great correlation between the operating parameters with ash content and combustible recovery (CR). The drum speed indicated to be significant factor on the separation efficiency and the shake amplitude was found to be insignificant. Again Chaurasia et al., (2018) did work on the beneficiation of fines to investigate the effect of operating parameters, but this time with drum inclination as an additional parameter. The levels of these parameters were set to achieve yield 74.59%, combustible recovery of 84.56% and ash value of 19.22% from a coal feed of 33.5%. MGS operating parameters were investigated with the aid of pre-enrichment stage using a hydrocylone to treat coal tails of -0.5mm. The hydrocyclone was able to produce a clean coal ash of 42.60% from 54.82% with improved calorific value of 2573kcal/kg from 2279kcal/kg initially. Again, the effect of drum rotation, wash water rate, drum slope and pulp density were investigated on final stage of enrichment using MGS. Through the optimized parameters the calorific value of 3226kcal/kg, % ash of 24.21% with a coal yield of 36.16%(Özbakir et al., 2017).Table 1 shows that the testwork mentioned above show similar operational parameter set value application to be able to achieve high concentration performance. All these operational parameters can only be governed by the coal characteristics and mineralogy, not only can a fixed set of operational parameters can give the same out-put variable. For example, a study was done on the Optimization of a Multi Gravity Separator to produce clean coal from

Turkish lignite fine coal tailings i.e. Tuncbilek and Soma tails in Turkey, the two coal samples were treated at the same conditions but their optimal output parameters where different. The ash content and clean coal recovery of Tuncbilek tails increased with increase in drum speed, while on Soma tails there was no significance of increase in drum speed, however the recovery of clean decreased with an increase in drum speed. The studies above mentioned showed that the tilt angle plays a major important role, in the case of the Tuncbilek and Soma tails tilt angel was found to be insignificant(Özgen et al., 2011). In other instances, the MGS is used together with a hydrocyclone and treats the underflow product, the question now is what value of coal the overflow contains if not treated?

Table 1: Set of operational variables obtaining high concentration performance regardless of the feed characteristics

	(Oluklulu and Koca, 2018)	(Chaurasia et al., 2018)	(Özbakir et al., 2017)
Required outputs/ Produced outcomes	CR of 50.81%, ash reduction from 75%-50.81% and improved calorific value from 2072kcal/kg from 1490kcal/kg	CR of 84% and % ash content of 19.22% from 33.5% with yield of 74.59%	Calorific value of 3226kcal/kg with % ash of 24.21% and coal yield of 36.16% with the aid of hydrocyclone as a pre-enrichment
Bowl speed/ Drum speed	Highest level	280	225
Shake frequency	Highest level	4.9	Kept constant at 4.9
Shake amplitude	Highest level	15	
% Solid	Lowest	10% by weight	10% by weight
Inclination	Not evaluated	3 degrees	4 degrees
Upward wash water		1 L/min	1 L/min

3.1.2 Knelson concentrator

Uslu et al., (2015) described a knelson concentrator as device that applied hindered settling related to hydrosizers that substitute gravitational force with centrifugal force (Coulter and Subasinghe, 2005; Erasmus et al., 2016; Majumder et al., 2007). Just like MGS, this also has operational parameters which govern its performance i.e. bowl speed, fluidization water flow rate, solid ratio and feed rate . The Knelson gravity concentrator operates at centrifugal forces up to manifold to that of standard gravity on the particles, catching high density particles in a progression of rings ,while the low-density particles are driven out of system through wash water(Wills and Finch, 2016). The feed pulp enters through a stationery tube into the concentrate cone(Majumder et al., 2007). The pulp becomes constrained as it arrives at the bottom of the cone. Fluidization water is brought into the concentrated cones through a progression of fluidization gaps. The slurry completely fills each ring making a concentrate bed, with compaction of the bed counteracted by the fluidization of the water. The progression of water is infused into the rings is controlled to accomplish ideal fluidization water. High explicit gravity particles are caught and held in the concentrating cone; this material particles can be substituted for the low-density material that was beforehand in the riffles (this is made conceivable by the fluidization water of the bed). At the point when the concentrate cycle is finished, the concentrates are flushed from cone into the concentrate wash.

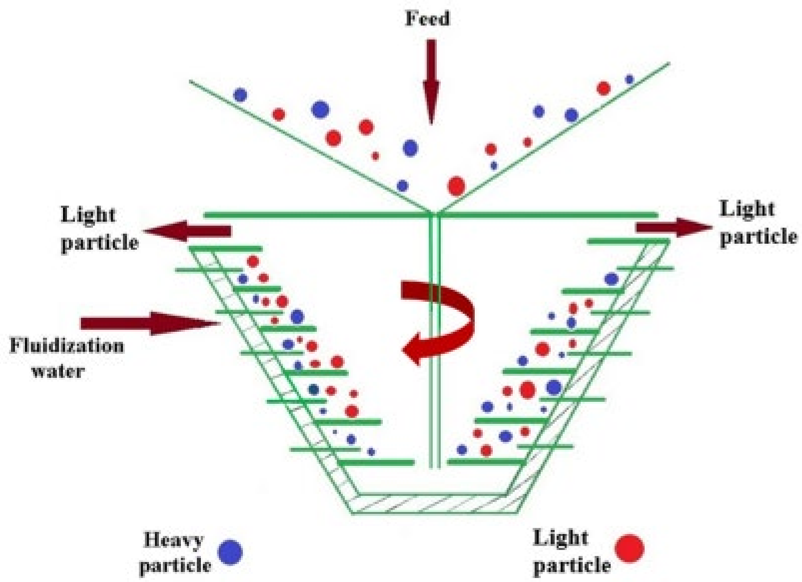

Figure 3: Schematic illustration of operation principles of Knelson concentrator (Fatahi and Farzanegan, 2017)

Oney et al.(2017) studied the operating parameters of Knelson concentrator and investigated them at different ranges with the aid of upgrading curves. The upgrading curves in the study suggested that the Knelson concentrator can be used to recover fine coal effectively with technical applicable advantages as a clean coal product of 12% ash from 24% of the feed was produced at 79.33% and 91.95% of combustible recovery. The study also reported that at those conditions had a significant improvement in calorific value as it increased from 5412kcal/kg to 6592kcal/kg. The findings denoted by Oney et al.(2017) were supported by the work that Ma et al. (2018) wherein investigation carried out using CFD-DEM modelling was applied and simulation results demonstrate that the division proficiency expanded with diminished centrifugal force at steady fluidization water and increments with expanding the fluidization water rate at consistent centrifugal force generated. In this case the centrifugal force is associated with bowl speed. The use of applying numerical simulation using CFD-DEM in the study also showed that it can be applied in the design and optimization of Knelson concentrator. The findings of the two works are summarised in Table 2.

Table 2: Comparison of correlating findings between studies done by (Oney et al.,2017) and (Ma et al.,2018) on Knelson concentrator

	(Oney et al., 2017) Ranges studied	**(Oney et al., 2017) Optimized values**	(L. Ma et al., 2018) **Remarks from CFD-DEM numerical analysis**
Bowl speed(rpm) *(Centrifugal force)*	250-1250	459	Expanded partition proficiency with diminished centrifugal force at predictable fluidization water
Fluidization rate(L/min)	2-4	3.14	Expanded partition proficiency with expanding fluidization water rate at steady centrifugal force

The same applied on MGS , Sabah & Koltka (2014) had already applied i.e. a pre-enrichment treatment of coal fines using hydrocyclone. Knelson concentrator was used applied on hyrocyclone underflow material from pre-enrichment stages to examine the impacts of bowl speed, fluidization pressure, sample time and solid concentration. The product ash of 30.51% and calorific value of 4259kcal/kg with separation efficiency of 19.50%. Regression model generated designated that bowl speed, sampling time and pulp density to outcome are avoided and that their expansion while lessening the fluidization water improves ash level in the product. Low level ash in clean coal was not acquired with high productivity partition. To build the effectiveness of division Knelson concentrator ought to be worked at hindered settling. A dense and viscous medium had to be tolerated to change separation condition from particle size to specific density dependent and this was done by operating at increased solid concentration of 40%. One greater limitation generated from such an experiment is that the overflow material from hydrocyclone is left untreated which means that again the method has its own limitation. Even though flotation is considered to be expansive process one would suggest that the cyclone overflow should also undergo treatment with flotation or even with the use of agglomeration.

3.1.3 Falcon concentrator

Designed for the recovery of free gold in the grinding circuit classifier underflow is a spinning batch concentrator known as falcon concentrator. Its biggest advantage is that it generates centrifugal force of around 300 to 600 g's which allows for lower density cut point and high throughputs as compared to other Enhanced gravity separators discussed above which enable higher density cut points of 1.9 to 2.1 because they lack the to ability to provide centrifugal force six times greater than that of natural gravity(Boylu, 2014; Honaker et al., 1996). Material stratifies in accordance to particle density as feed slurry is introduced before making way to concentrated bed fluidized by back pressure (Honaker et al., 1996; Wills and Finch, 2016) The bed holds dense particles and the lighter particles are washed over the top, occasionally the feed is halted, the bed is flushed to evacuate any residual lights and is then flushed out as heavy material product. The rising and flushing which is under programmed control is resolved from the grade and recovery prerequisites.

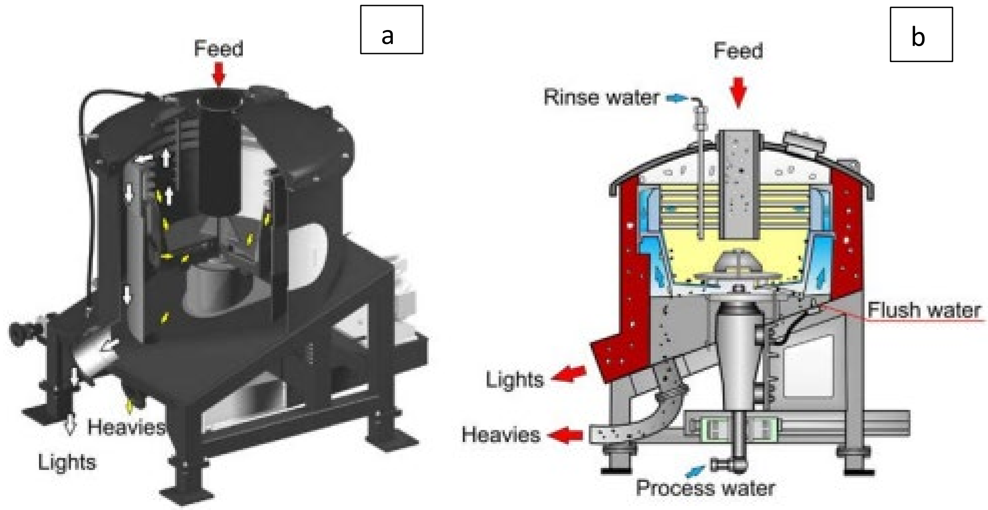

Figure 4: (a) Cutway view (b) Cross-section view illustration of falcon concentrator((Wills and Finch, 2016)

The effects of operational parameters was investigated by Oruç et al., (2010)upon the use of falcon SB-40 concentrator model treating tailings of ultra-fine coal of which 80% of the material is -20µm. The activity factors tried were bowl speed, water pressure, density of pulp and pulp feed rate were researched on. The work was done on a pre-enrichment two stage hydrocyclone product which was done to remove the slimes. What value does those slimes contain and what methods can be used to treat such material? Since the material being treated contained 80% -20µm, the falcon was found to ineffective in beneficiating the material. Falcon concentrator was able to produce coal product with 45.9% from 66.43% and increment in calorific value from 1449kcal/kg to 4224kcal/kg at optimized operating variables of 300g, 20% solid, feed rate of 1l/min and water pressure of 0.5 psi. However, the separation efficiency of 28.28% was reported which was poor and was accounted for that 80% of the sample particle size was -20µm. The feasibility analysis of gravity separation was studied by density composition analysis and results show that enhanced gravity concentrator can achieve the effect of desulfurization and deash; however, the efficiency is low. The low separation efficiency was revealed by separation performance of different size particles. Results illustrate that distribution rates of particles in clean coal increase with the decrease of size, and the existence of ultrafine fraction is the main reason for the high ash content of clean coal(Zhu et al., 2017) .However, work that had a solution to the low separation efficiency was answered by contemplating the impact of solid concentration and centrifugal force to distinguish ideal separating conditions. Boylu (2014) observed that that the solid concentration plays an important role and had significant improvements in separation efficiencies. The improved separation efficiencies are because of a switch in terms of method of separation. In this case separation method was changed from being size specific to density specific. The solid concentration is to be increased to 50-55% causing medium to be dense and viscous forming an autogenous medium. Partitions at autogenous medium s conditions accomplished sensible detachment efficiencies notwithstanding for the coal fines in size of −75 µm, which conveys the size division of −20 µm in over half of the feed.

Once coal has been removed from beneath the earth surface and crushed, it is prone to react with atmosphere which then cause physical and chemical change in properties of coal. The use of Falcon was found to much more superior than flotation on deashing and desulphurization of fine oxidized coal (Zhu et al., 2016); centrifugal force and water flowrate were investigated on and yield percentage of 53.86% and ash content of 9.81% from 34% and Sulphur of 1.47% from 2.95%. It was observed both parameters play an important role separation. The yields, ash content and desulphurization efficiencies of coal were decreased when greater centrifugal force is applied. Yields, ash contents and desulfurization efficiency of gravity clean coals increased with the recoil water flow with similar sulfur content. Particle group in separation area could be easily decentralized with the greater recoil water flow, leading to more light particles into the overflow.

The Knelson concentrator now becomes an answer to what the MGS could not do, the MGS separation efficiency drops with increased percentage solids, but the Knelson concentrator works best with high concentration of solid. What a comparison study would be beneficial to compare the two techniques at same operational level and again try and blend the two technologies.

3.2 Oil agglomeration

Coal agglomeration is a surface-based property method that includes the expansion of immiscible oil to coal-water slurry under unsettling bringing about coal-oil agglomerates. The contrast in wettability of the perfect coal particles and that of mineral matter by an agglomerant such as light and heavy hydrocarbons or non-hydrocarbon. This easily means that in accordance to the attributes of inorganic and inorganic particles, agglomeration can be used to remove inorganic material from the organic because of high selectively and separation efficiencies(Aktaş, 2002; Bensley et al., 1977; van Netten and Galvin, 2018; Xia et al., 2015).The hydrophobic coal particles are wetted with oil, yet not the hydrophilic buildup or clay particles. The coal particles at that point agglomerate into particles enormous enough to be isolated from buildup by sieving.

Unlike the application of froth flotation with limitation, oil agglomeration is the main procedure that successfully treat low rank coal and oxidized coal including size underneath 38µm (Sahinoglu and Uslu, 2015). One other great advantage is that there is a significant enlargement in size easing coal recovery, calorific value improvement and operation. Oil Agglomeration process is affected by factors such as coal type, particle size, type of oil, slurry pulp density, and ultrasonic treatments. Parameters optimized include Ph, oil concentration (oil dosage), agitation speed, temperature and agglomeration time. The parameters are optimized so that the percentage contribution towards organic matter recovery can be observed.

The previously mentioned operational parameters which are particle size ,agitation time, oil type, slurry Ph, pulp density, agitation rate and measure of wash water were examined on removal of ash and Sulphur from coal tailings(Yaşar et al., 2018). Results from this work done show that there is indeed potential in the use of this technique as it shows promising results as illustrated in Figure 5 below of concentrate having less mineral matter compared to that of the feed. Since oil is one of the major drawbacks in the use of agglomeration because of high cost, the study also focused on using waste sun flower to determine whether it could have an upper hand over high-quality oils such as fuel oil, diesel oil, motor oil and kerosene. The waste sun flower oil was observed to be a decent decision of low cleaning coal utilizing oil agglomeration. The side effects of each parameter are summarized in structed Table 2. It was found that that operational in testing parameters have an effect in the performance of fine coal cleaning and the results

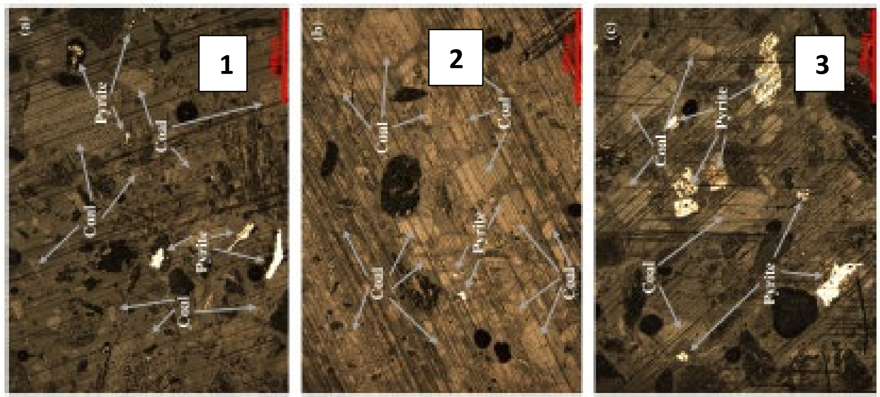

Figure 5: SEM-EDS results of the (1) feed (2)concentrate and (3)tailings product of agglomeration process(Yaşar et al., 2018)

Table 3: Summary of remarks of each operating variable component.(Yaşar et al., 2018)

Operation Parameter	**Remarks**
Agitation rate	An increment in agitation rate increases the recovery of combustible matter, ash and sulphur. However, after 1400rpm the ash rejection starts deteriorating
Solid Ratio	An increase in solid ratio concentration increases the combustible recoveries because of improved contact angle between oil droplets and coal particles. Ash rejection to clean coal however is not improved as solid concentration is increased.
Dosage	An increment in oil dosage increases recovery of combustible matter because improved contact of coal with oil and the arrangement of bigger number of

	agglomerates by increment in number of oil droplets in the slurry.
Amount of washing water	Increase in amount of wash water showed a decline in combustible recovery
Agitation time	Increased agitation tends to decrease the recovery of combustible matter. Because of increased residence time this led to the breaking of insecure agglomerates.
Slurry pH	Increasing slurry Ph from acidic to neutral media improves combustible recovery matter. When the pH moves from neutral to basic media conditions, deterioration of combustible recovery and ash rejection is observed
Oil type	Higher combustible recovery was achieved by using waste sunflower oil for which this resulted to the to its attributed higher density in contrast with other fuel oils
Particle size	As the particle size of coal decrease, this improves the ash rejection however, a decline is observed in combustible recovery and removal of Sulphur

No industrial application for this technique has been applied in this process because of escalated pricing of oil that makes the process economically unfeasible. Waste mustard oil was used to agglomerate fine coal together with the impact of agglomeration duration, oil dosage and solid concentration (Shukla and Venugopal, 2019). A recovery of 99.96% organic matter and ash rejection of 62.56% was obtained showing that it has good agglomeration properties. Again, stressing the worsened economics of the process, incite studies were conducted to minimize oil dosage to counter act the worsen pricing of oil, and out of that study a recovery of 79.21% organic matter and ash rejection of 65.41% ash was obtained at 8.39% oil dosage. This shows that waste mustard seed oil is an outstanding bridging liquid than the presently utilized oils in the market. Other types of oils were further explored by Yadav & Suresh (2016), which were linseed oil, castor oil, refined soybean oil and karanja oil.The order of % organic matter recovery was found to be linseed oil(because of good selectivity)>karanja oil> refined soybean oil> coster oil and for % ash rejection was found to be linseed oil> refined soybeans> castor oil

>karanja oil. Yadav et al., (2018) did a studied the application of different oils from different sectors looking at operation parameters such as oil dosage, agglomeration time and pulp density .The optimal conditions for selected was pulp density of 3%, 15% oil dosage, agglomeration time of 15 min using waste engine oil with corresponding % ash rejection and % organic matter recovery at 81.80% and 77.70% respectively. The ash rejection was found to have an increase with increasing oil dosage and decreasing pulp density. The order of significance of % ash rejection was as follows pulp density>oil type>oil dosage>agglomeration time and the order of significance of % organic matter recovery was pulp density> oil dosage> agglomeration time>oil type.

Other modification has been done to progress from the use of conventional oils to utilizing water-in-oil emulsion as an immiscible binding liquid. This includes the utilization of high inward stage emulsion as it gives the interfacial usefulness of the oil while the spaces filling the usefulness is given by the balanced out inside water droplets and the application is illustrated in Figure 6 . Van Netten et al., (2015)studied the kinetics of modified fine agglomeration and did an investigated with an aim of minimizing the quantity of organic liquid used in the process and this was done by comparing water-in-oil emulsion with conventional diesel. The influence of binder dosage was investigated, and both binders showed the same trend as illustrated on Figure 7.

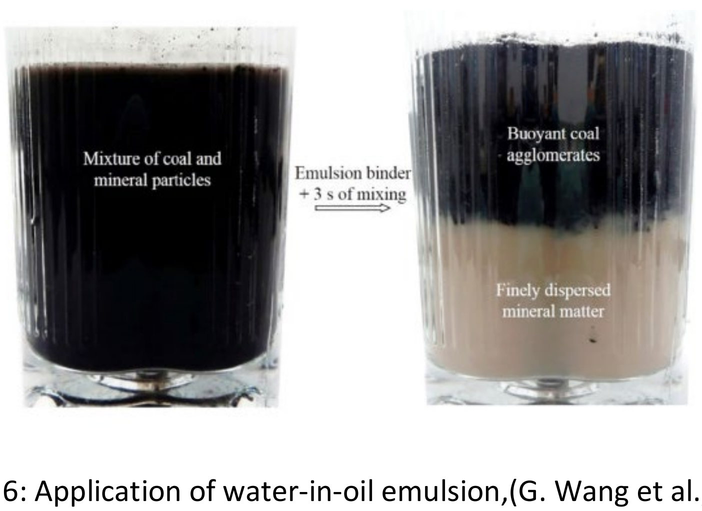

Figure 6: Application of water-in-oil emulsion,(G. Wang et al., 2018)

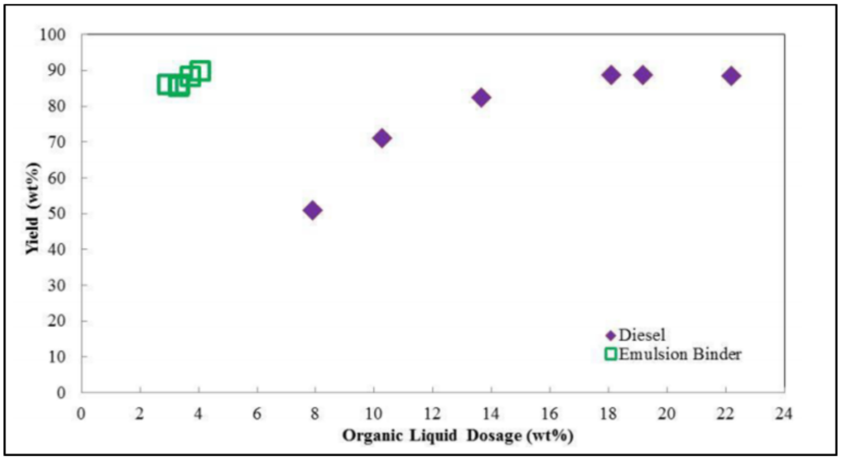

Figure 7: The influence of binder dosage on % yield, Source(Van Netten et al., 2015)

Maximum yield of 90% was achieved at dosage of 4% for emulsion binder and 20% for diesel, meaning that the emulsion organic liquid requirements have been reduced by factor of five to fully agglomerate the feed and that one fifth of the natural fluid is required when unadulterated oil cover is utilized. Results again demonstrated that the for full agglomeration of the feed, emulsion folio does it in 33% of the time required by unadulterated diesel cover. The Kinetics was examined by passing the agglomerated on arranged screens for example 150um and 355um. The blue being emulsion fastener and red being diesel folio on figure 8. Figure 8(a) demonstrate that the base worth speaks to the mass portion of ultrafine molecule minerals in the feed that are not wetted by hydrophobic covers and remain finely scattered in the slurry. Figure 8(b) shows increase in mass of agglomerates when diesel is used as a binder. A sharp decrease in amount of agglomerate was noticed when emulsion binder was used which suggested that material has already exceeded size of 355um. Figure 8(c) shows that rapid growth of agglomerate when emulsion binder is used compared to slow growth when diesel binder is used. Since production is affected by time, emulsion binder proves to minimize the agglomeration compared to the application of diesel as agglomerant. Even if this process is faster, how economical is it to in production perspective.

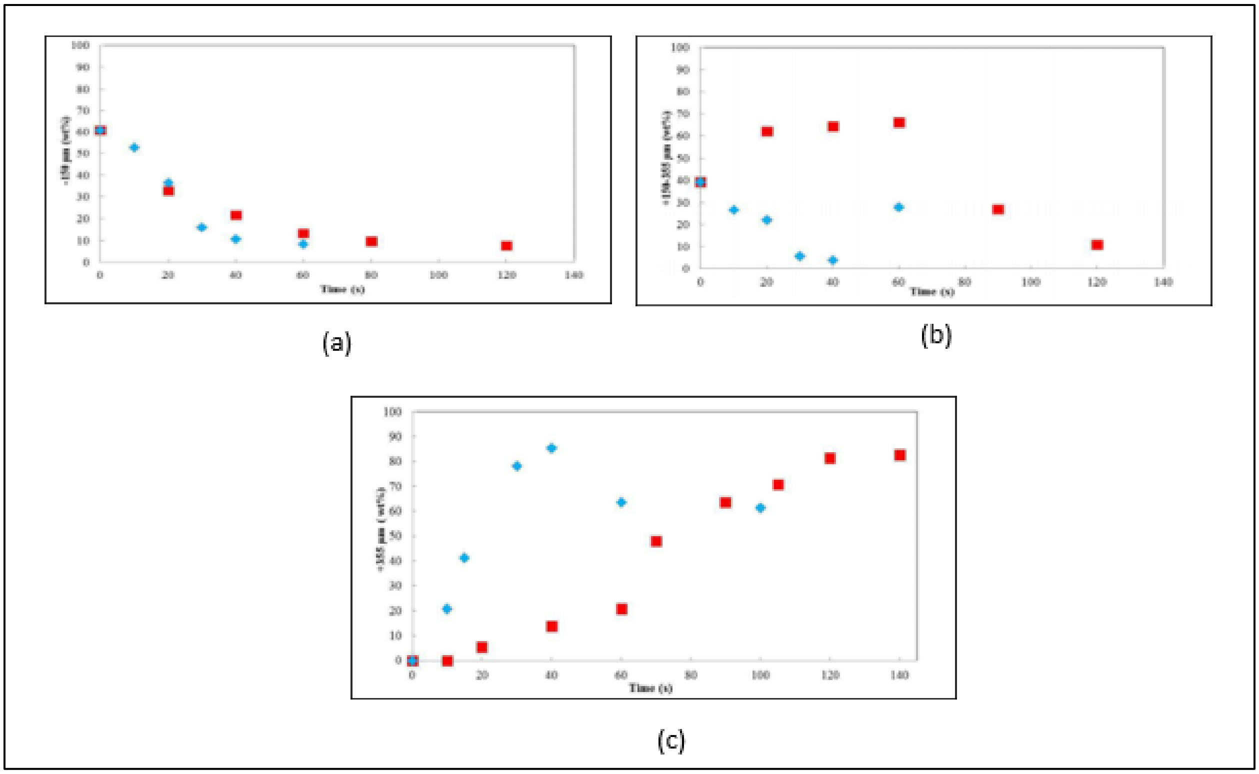

Figure 7: (a) change in mass percentage of -150um size fraction with time (b) change in mass percentage of +150 – 355um size fraction with time and (c) change in mass percentage of +355um size fraction with time, Source,(Van Netten et al., 2015).

With all the good work done on agglomeration of coal fines, such works includes the above mentioned which are the use of waste oil and development of bridging agent binders, effort need to be made to put such a technique in pilot plant. It's understandable that the commodity of coal is too cheap to be treated using an expensive process, but one needs to look at the aftermaths of not using the coal at correct standards. And again, the overflow material from pretreatment stages to remove ultra-fine coal prior the use of enhanced gravity separation as discussed previously could be applied in the study of oil agglomeration to evaluate its effectiveness in cleaning the ultra-fines. Could somehow lessen the limitation of enhanced gravity separation methods as they cannot treat slimes.

3.3 Flotation

Coal flotation is the most proficient technique to improve the nature of fine particles by diminishing pollution substance (Azizi et al., 2014; Majumder and Barnwal, 2011). The hypothesis of froth flotation is mind boggling and isn't totally comprehended. This reality has been brought many observing difficulties in a coal preparation plant (Ye et al., 2017). To tackle those difficulties, it is essential to comprehend the impact of various parameters on the fine molecule partition, and control flotation performance for a system execution. Parameters explored are categorized into 3 which are coal of which particle size distribution is considered to be the most important, chemistry and machine and this include reagent addition, aeration rate, pulp density, and degree of agitation(Cheng et al., 2013; Li et al., 2013; G. Ma et al., 2018b; Parekh, 2003; Qu et al., 2015; Sahinoglu, 2018; Y. Wang et al., 2018). By and large, flotation depends on the distinctions of the coal and pollutions surface compound attributes. Coal is a heterogeneous material which made out of an assortment of natural segments (macerals) and inorganic parts (Mineral issue) that react distinctively to flotation. In this way, surface properties and flotation reaction of coal tests are altogether shifted, and it is imperative to see how various elements influence and how to control coal flotation performance for as system.

Various operational parameters mentioned above play a key essential role in achieving highest concentration performance of floatation method i.e. maximizing the % ash rejection in clean coal and the yield. Ye et al. (2017) explored other key features such as stirring time reagent dosage of frother (sec-octyl alcohol), collector(diesel) to assess the impact on the flotation perfect index (FPI)-which is used to examine the performance of flotation for specific slime, and the ash content. It was found that collector dosage significant interaction with ash content while FPI has strong interaction with the stirring rate.

Reagent consumption is a major contributor to drawbacks techniques used to treat coal, because of the value that coal is rated at, therefore it would be of poor economics to make process expensive by using expensive reagents in the process. Squander colza oil from cooking industry was utilized as an elective gatherer for recovery of ultrafine low rank coal by flotation (Xu et al., 2019). The yields using waste colza oil were higher than the use of diesel especially at high dosage i.e. yields of 35.68% and 5.54% for colza oil and diesel respectively at maximum dosage 6kg/t. Improved floatability and floatation recovery was ascribed to the hydrogen bonding between oxygen-containing groups in waste colza oil and low rank coal surface. Xia et al., (2019) used lubricating oil (ULO) as collector to go against the use of expensive diesel and it has proven the application of the used lubricating oil can indorse low rank coal flotation because of the following findings; Lubricating oil ascribed to containing more oxygenated functional groups, aromatic group and long chain hydrocarbons than diesel prompting solid association with the low rank coal. Moreover, the science behind ULO as a flotation was analyzed and found that the adsorption of ULO expanded the carbon content and diminished the oxygen content on the low rank coal surface. This is advantageous as it diminishes coal-water association; this then allows ULO to demonstrate more grounded connection with the coal, and coal particles pre-treated with ULO all the more effectively hold fast to the air pocket surface. Instead of using waste oil, Yang et al., (2019) applied pretreatment on fine coal using compression and investigated the impact of pore structure on collector adsorption and flotation of low rank coal since large structures and rich pores on the surface of the coal have been reported to reduce the efficiency of separation when using flotation techniques on low rank coal. With compression pressure of 400Mpa and pretreatment using n-dodecane as collector, 74.44% maximum coal yield was obtained which is 20.46% points higher than that of raw coal flotation using n-hexane collector. In the same study a collector that is too viscous and has short carbon chains is responsible for total cumulative yield of low rank coal to decrease. Many publications consider floatation to have its own limitations in application of fine coal treatment because of its poor economics of reagents consumption but if the world is really concerned about carbon foot-print it would consider the application of such technologies regardless of the cost especially for the treatment of ultra-fine coal material

3.4 Gravity separation

3.4.1 Water only cyclone

This gravity separation equipment has been defined as gravity concentrator that uses water as a medium of separation(Majumder and Barnwal, 2011; G. Wang et al., 2018). WOC is traditionally used in coal sector to treat material that is less than 0.5mm(Tripathy et al., 2017) This becomes an advantage as it operates at high capacity with no other external medium for separation and no moving parts during the cleaning process. It is attributed with elongated vortex finder, elongated cylindrical section and a wider conical bottom angle which makes it easy for material to start building up and allowing which hindered settlings conditions to prevail as illustrated in figure 9 (Tripathy et al., 2017). Figure 9 displays main difference between WOC and classifying cyclones

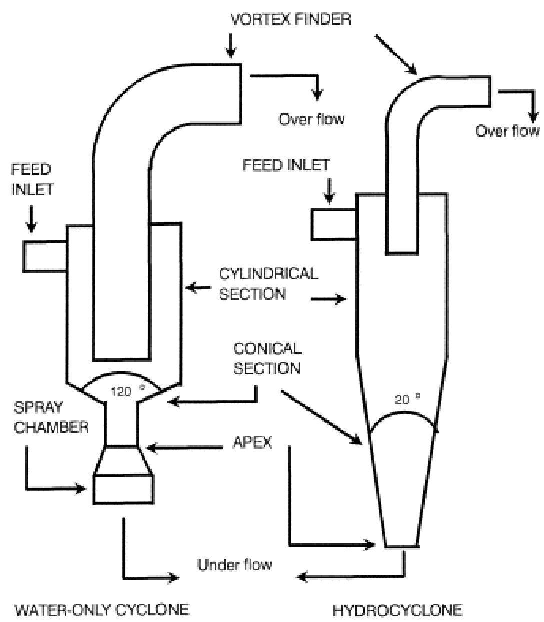

Figure 9: Illustration of difference between water only cyclone and hydrocyclone classifier, Source:(Patil et al., 1997)

The feed introduced to the WOC tangentially and hindered settling conditions prevail thus creating a dense bed of particle which is ascribed to minimized movement of particles down the wide conical section of cyclone. The dense bed created makes it difficult for lighter particles to pass through therefore reporting to overflow through vortex finder. The denser particles builds up and is discharged through the apex(Flintoff et al., 1987; Patil et al., 1997).

Majumder & Barnwal (2011) studied design parameter variables on the performance of water only cyclone with the assistance of regression models to quantify the parameter effects. Operation design parameters which includes cone angle, vortex finder diameter and vortex finder length was studied at constant pulp density of 10%, feed inlet pressure of 0.7kgf/cm^2 ≈ 68.6466Kpa and spigot diameter of 20mm. The regression model showed that the influence of all individual variables was positive meaning that an increment on an individual parameter tested parameter would result in an increment in the yield in clean coal and ash content in clean coal. Amongst the three variable parameters tested the vortex diameter was found to be the most sensitive as the level of order increased from vortex diameter to least sensitive the vortex finder length for ash content on the clean coal and the yield of clean coal. It was also observed that the efficiency of separation drops significantly to separate fines (-0.075mm) based on density due to the fact that the pressure drop created inside the system if sufficient enough to report fines to overflow thus increasing the ash content.

Development have been done on the water only cyclone which has led to the birth of modified water only cyclone. The table 4 and figure 10 below illustrate the difference between the two water only cyclone. In this study optimization of parameters i.e. cyclone diameter, apex diameter and vortex finder diameter of both the classical water only cyclone and modified water cyclone were compared(Hacifazlioglu, 2012).

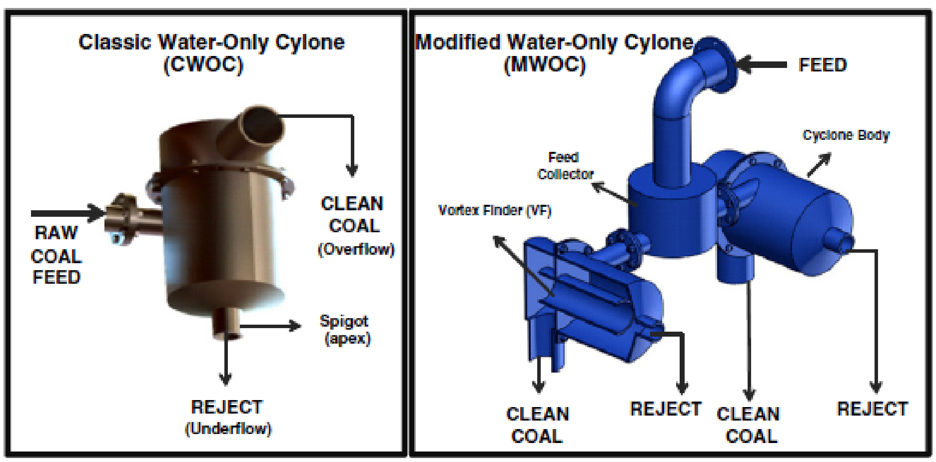

Figure 10: illustration of classic water only cyclone and modified water only cyclone

Table 4: Comparison between the modified water only cyclone and classical water only cyclone generated from (Hacifazlioglu, 2012)

	Modified water only cyclone	**Classical water only cyclone**
Orientation	Horizontal position	Vertical position
Separation method	Size based separation	Density based separation

Out-put product	Homogenous size	Heterogeneous size
Number of cyclones	Double cyclone	Single cyclone

An increment in the cyclone diameters of both cyclones resulted in an increment of ash content in clean coal. A decrease in pressure is noticeable with increased diameter which means that the intensity of centrifugal force generated on particles drops, thus decreasing the effectiveness of separation. Little effect was observed on the coal yield as small average increase in coal yield. Increase in the diameter increases vortex finder diameter which is considered most delicate parameter in the previous study would results in an increase in coal yield and increased ash in clean coal because increased amount of material to cyclone overflow.

3.4.2 Spirals

The spiral concentrator applies differential density separation between particle particles thus to separate the valuable minerals from the gangue minerals. They have been widely utilized in coal washing plants worldwide to treat material in the particle material that is regarded as waste and ranges from size of 1mm-150 micron (Other reports show that spirals are capable of treating material down two 45um). Material of such size range is too coarse to be treated using froth flotation and too fine to treat in large diameter heavy medium cyclones(Atasoy and Spottiswood, 1995; Holland-Batt, 1995; Honaker et al., 2007; Mohanty et al., 2014; Shi et al., 2018). The major factors that makes this concentrator attractable for its application is low capital and operating cost, higher recoveries with no reagents used.

Even with the application of wide diameter, spirals have inability to obtain a D_{50} lower than 1.65 but tend to have a D_{50} of 1.7-2.1 for which therefore misplacing significant amount of ash fines in to the clean coal. The D_{50} can be further reduced by reducing the feed rate, but that is not economically healthy or done by utilizing two stage spiral in series platform, but such a setup is still not sufficient to obtain a fine coal a 10% ash value product(Barry et al., 2015; de Korte, 2016; Shi et al., 2018; Ye et al., 2018). Development of LC3 spiral model is capable of obtaining separation cut point densities lower(1.4-1.55) and similar EPM values to spiral being used(de Korte, 2016; Palmer, 2016). From the Figure 11 below, the LC3 spiral model obtained low ash level in both the middling streams clean coal product and; such results show that LC3 spiral model has greater separation at both the low D_{50} and high D_{50}.

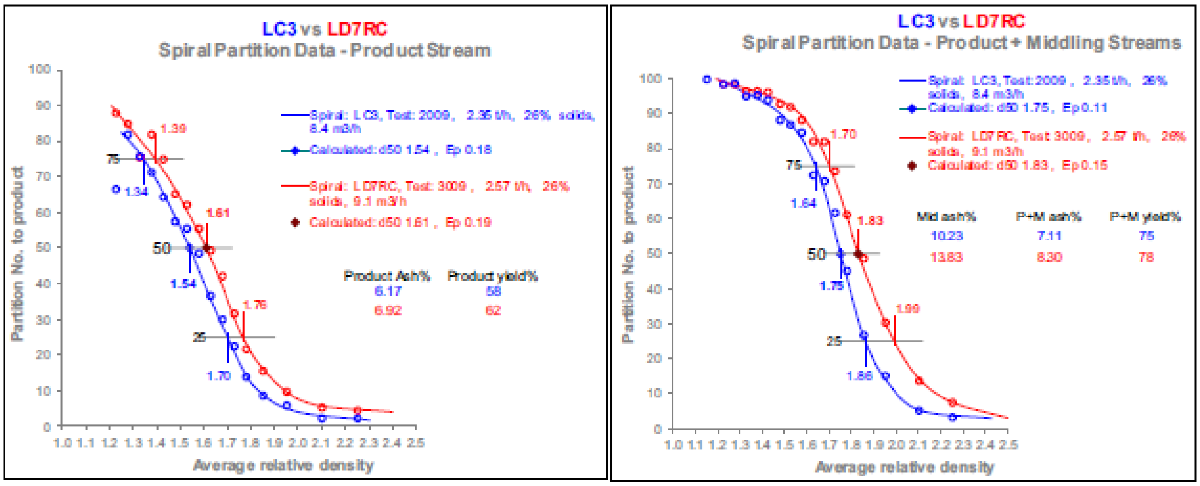

Figure 11: LC3 vs conventional LD7RC,(Palmer, 2016)

With limited work being done on the structural parameter of spiral, Ye et al., (2018) studied trough profile of the spiral on separation performance of fine coal. Since too much attention is given to the particle size distribution ,feed rate, solid concentration and splitter position(Gulsoy and Kademli, 2006), work was done by studying three trough profile which is of ellipse, cubic parabola and synthetic curve as shown in Figure 12 below an illustration of how the trough looks like, this troughs were under operational variable which include flowrate and solid concentration(Atasoy and Spottiswood, 1995; Kapur and Meloy, 1998; Kwon et al., 2017; Ye et al., 2018). It was observed that coal tends to move to the peripheral end of the spiral as the feed rate and solid concentration increases the D_{50} also increases with feed rate and concentration of solids. Spiral concentrator with the elliptical profile is preferable to collect the light particles in outer place, while spiral concentrator with the trough profile of cubic parabola is effective for the accumulation of heavy particles in the inner region of the trough. The spiral concentrator with the trough profile of cubic parabola in inner place, together with the elliptical profile in outer place, is more desirable to separate the coal slime used in this paper.

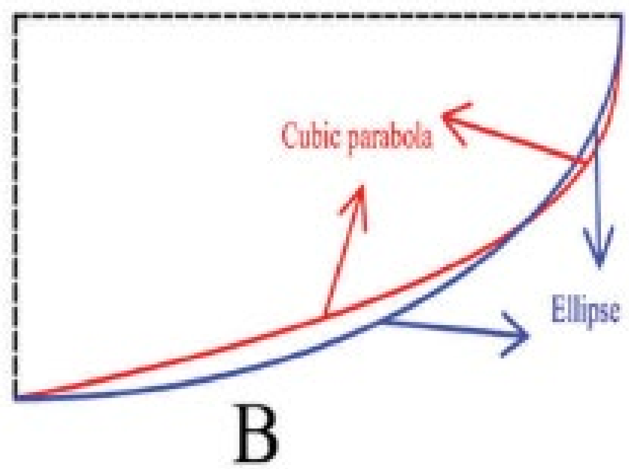

Figure 12 : Illustration of variation between cubic parabola and ellipse trough profile, source(Ye et al., 2018)

3.5 Flocculation

This is a method used for dewatering and settling of fine solids of which its main objective is get clear water with low percentage concentration of solids(Sabah et al., 2004; Zhichao Yang et al., 2019). With the development in cleaning coal fines and ultrafines it has shown that obtaining coal of low ash and low sulphur contents is feasible nowadays. However, the commercialization of these technologies is hindered, partly due to the poor efficiency of dewatering circuits for fine coal slurry because this processes involve some difficulties attributed to the presence of colloidal particles of different shapes, sizes and specific gravities and their unique behavior in an aqueous environment(Kumar et al., 2014). Operating parameters such as pulp density, flocculant dosage and Ph are the operating parameters taken into account when such a process is applied and turn to be somehow sensitive to performance indicators such as settling rate and turbidity.

Separation efficiency equation developed by where R_m is the % recovery of valuable mineral and R_g is the % recovery of gangue illustrated by equation 1 , was used to develop settling efficiency equation(separation of solid and liquid) thus to analyze the efficiency of dewatering and was termed settling index as illustrated by equation 2 and the assumptions made during the formation was the solids is considered to be the concentrate, the water(liquid) considered as waste and the solid content of the supernatant liquid set to be zero. The index was defined as the difference of percentage recovery of solids in the settled slurry (Rs) and the percentage recovery of water in the settled slurry (Rw),(Kumar et al., 2016b).

Separation efficiency(SE) = $R_m - R_g$ ……………(1) (Schulz, 1970; Wills and Napier-munn, 2006)

Settling index(SI)= $R_S - R_w$……………(2) (Kumar et al., 2016b)

Modification of the settling index equation with the introduction of % solids in the feed and % solids content in the settled slurry led to the development of settling index curve illustrated in the Figure 13 which can be used to assess the performance of the thickener, if 4% solid is contained in the feed 32% solid concentration to the underflow this means that settling index is at 95%. This has also been used to for respective parameters that are applied in flocculation i.e. flocculation dosage, pulp density and Ph.

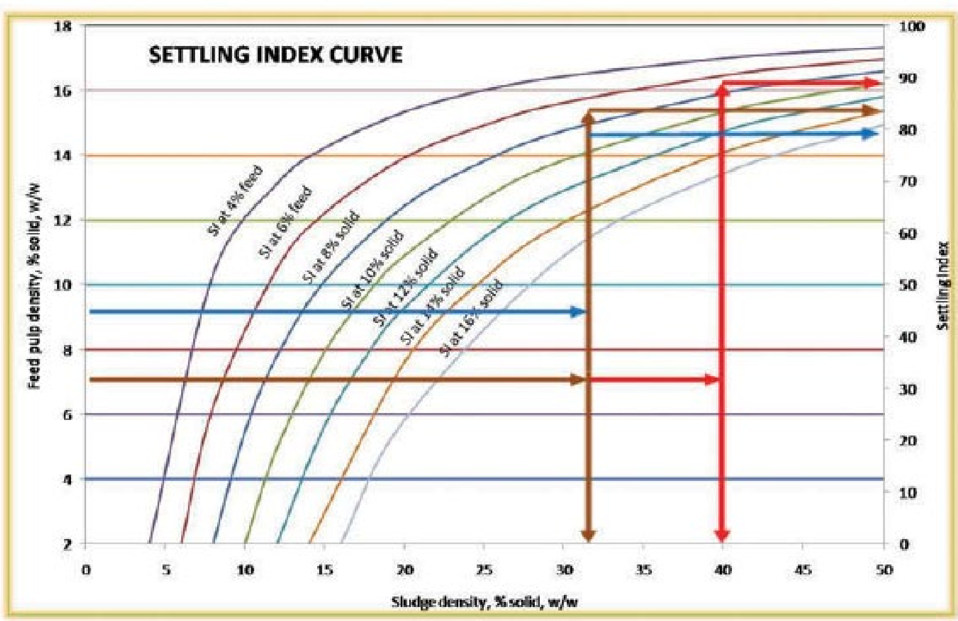

Figure 13: Settling index curve(Kumar et al., 2016b)

With the assistance of Box-Behnken design methodology, performance optimization with reference to the settling rate was conducted on variable parameters i.e. pulp density, Ph and flocculant dosage(Hansdah et al., 2018). Using 3D response surface methodology, it shows that an increment in both the pH and flocculant dosage increases the settling rate, this was reported to be attributed to enough polymer adsorption on the particle meaning that more suspended particles participate in the flocculation and again the high dosage increases settling rate owing to increase in floc size. Further increment in the flocculant dosage plateaus the settling rate because the presence of additional charges in solution cause electric repulsion between the floc. A decrease in flocculant dosage and increase in pulp density decreases settling rate owing to hindered settling scenario because low dosage makes floc size to be small because of insufficient polymer adsorption. Lower pulp density and high pH increases the settling rate. however, Kumar et al., (2016b)reported that increasing pulp density and pH increases the settling rate The mentioned opposing statement could be as result of the type of polymer used((Hansdah et al., 2018) applied the use of high molecular weight cationic polyacrylamide polymer while (Kumar et al., 2016a) applied the use high molecular anionic polyacrylamide. (Kumar et al., 2016b) observed that the settling rate increases with pH from 4 to 8 like in their studies mentioned above, a further increment in the pH beyond 8 resulted in a drop in settling rate because of their changes in the charge characteristics of the polymer chain and structure in the solution which then directly affects the flocculating power of the polymer. Since the is coal fines attributes a study on the application of different coal could be beneficial to understand how the geology can link up with the selection choice of polymer together with other parameter variables in order to maximize settling rate and minimize the turbidity.

3.6 Dense medium cyclones

A comparative study was conducted on the treatment of fine coal using dense medium cyclone (DMC) and spirals, the DMC was found to be superior that the spirals in treating coal material of -1+0.125mm material as it obtained higher coal yield, combustible recovery, the high centrifugal force was main factor behind the DMC outperforming the spirals(G. Ma et al., 2018a). The performance between the two separation techniques was justified by applying Fuerstenau upgrading curve of which an equation was used as a measure of selectivity of separation. As illustrated in Figure 14, a relationship curve of the combustible matter in concentrate and the ash recovery in the tailings of the two techniques are plotted and compare which meets the ideal separation conditions best.

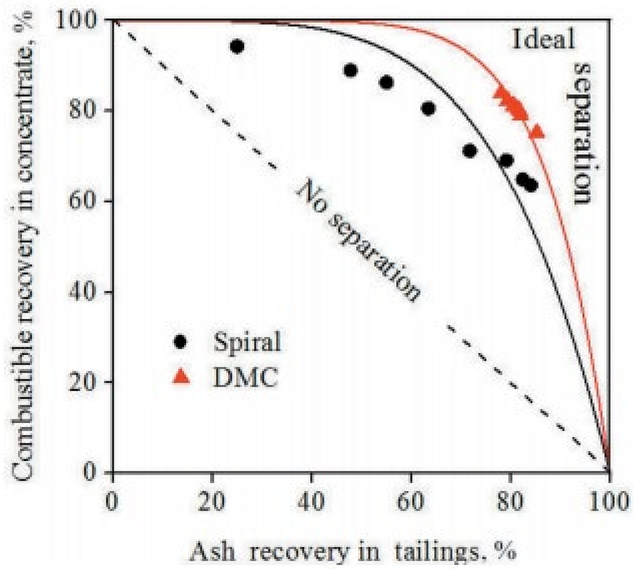

Figure 14: Fuerstenau upgrading curve of spiral and DMC (G. Ma et al., 2018a)

Since the separation efficiency of large-diameter cyclones with greater handling capability in fine coal treatment is questionable Liu et al.,(2018) studied the separation of 0.75–0.125 mm Fine Coal using the cylindrical section of a 710/500 mm Three-Product Dense Medium Cyclone. The separation efficiency was sharp at relatively low feed pressures and separation effect increased with increased feed rate. Since small diameter cyclones were preferred in industrial application, this study shows that fine coal can now be treated using larger diameter cyclone for improved through puts in the plant. The cyclone is in a series of stages with the first stage being 710mm column and the second stage being 500mm conical cyclone illustrated in figure 15. In terms of operation, the slurry is introduced in the column cyclone, and the overflow is considered as clean coal, the underflow from column cyclone flows to the conical cyclone. The second stage produces underflow(Tailings) and overflow(middlings), in some cases the two products are remixed to form one product again meaning that it becomes a 2 product cyclone again as it shows that separation effects on the second stage are not that effective for example, the differential density of underflow and over flow at no point surpasses 0.03g/cm3, while the product ash differential is hardly above 3%(Liu et al., 2018)

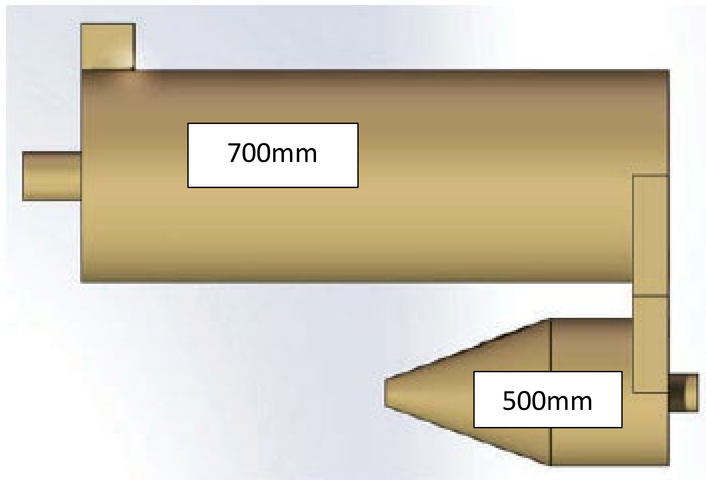

Figure 15: Illustration of diagram of 3-product cyclone designed by WeiHai HaiWang Hydrocyclone Co. Ltd, (Liu et al., 2018)

4. Conclusion

- It is possible to treat the waste fine and ultra-fine technologies using variety of methods, be it physical or physiochemical methods. The only major concern is that coal commodity is to cheap to be treated using an expansive process at higher rates. To be able to reduce carbon foot print and other negative effects of utilizing coal fines is either to apply the work that has been done to improve the quality of coal or rather do away with it being major building block of worlds economy. If some countries still, consider it as major contributor in its economy then something must be done about it because the aftermaths of ignoring this idea is massive.
- The application of statistical analysis and modelling also plays a key role in the techniques used to treat coal fines and ultra-fines. Studying the treatment options under statistical analysis allows observation of interdependencies of variable parameters of equipment without put variables such as coal yield and percentage ash rejection which allows a good understanding of treatment option.

- Coal characteristics play an important role with regards to treatment option, with such generation of data from the past, a model generated would be vary applicable to determine the operational parameters of method of treatment since coal characteristics are always changing
- All the above-mentioned techniques have shown improvement in over some years, application of waste oil in flotation and oil agglomeration. The application of water-in-oil emulsion binders shows to agglomerate waste fine coal quicker than diesel. The application of bio waste oil in both oil agglomeration and flotation shows that, these processes can be made economical. Pretreatment stages such as compression of pore structure of the coal enhances the floatability of waste coal.
- Development of LC3 spiral model demonstrated that low density cut points can now be attained when treating fine coal.
- Introduction of modified water only cyclone, of which it was found that design parameters still play an important role in effective separation as in traditional water only cyclones. The vortex finder was still found to be sensitive parameter
- Density based separation was found to be of good thought, when working with enhanced gravity separators i.e. hindered settling is far required to improve the efficiency of the process. Knelson concentrator was found to applicable in treating oxidized coal, which floatation techniques show greater draw back.
- Development of settling index curve was helpful to analyze the performance of sample settling and operational parameter investigated.
- 3 product cyclone with bigger diameter can be used to treat fine coal as opposed to the past as it was confined just to only small diameter cyclone. The application of Fuerstenau upgrading curve was observed to be helpful in assessing the performance of beneficiation equipment and has reported that dense medium cyclone still out performs spirals in terms of beneficiation of coal fines.

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