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Recent Trends in Mineral Processing Based on Density and Particle Size – A review

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Abstract

Most mineral beneficiation development in the world focus on size and density-based separation technologies. In recent years, ore size-based and density-based separation technologies have attracted more consideration to obtaining rough or final high-quality products. Due to the dissimilarity of physical properties like particle size and density, valuable and gangue minerals can be segregated via size-based and density-based separation technologies. Removing the impurities and recovering the target minerals are accomplished by size-based separation technologies alone or are usually followed by cleaning processes utilizing density-based separation abilities. The density variation among valuable and gangue minerals leads to dissimilarities in settling velocity in a fluid medium (air or water) to promote the density-based separation process. In addition, the effect of density-based separation processes is strongly influenced by the range of particle sizes to be treated. This paper thoroughly reviews the literature on recent advances in various gravity and sizing separation technologies, such as cyclones, enhanced wet separation, and dry separation from theoretical and technical aspects.

Keywords: Cyclones; Enhanced separation; Size-based separation; Density-based separation; Dry separation.

1. Recent trends in cyclone separation

Size-based classification is usually needed to control the particle size range required for different cleaning technologies. Size-based separation techniques are alienated into two main categories: screening and classification. Screening is conducted to control sizes of particles coarser than 1000 µm, while classification is employed to achieve particle size separations below 1000 µm using cyclones. Screening can be engaged in different manners other than sizing such as scalping to remove oversize materials, draining/rinsing to remove fines and dense media, and dewatering to remove water from product particles. Also, cyclones such as water-only and heavy medium cyclones are employed for density-based separation. Whereas classifying cyclones are operated for size-based separation.

Cyclones have many industrial applications in mineral processing to separate particles into different sizes and/or densities. According to operation style, there are variousety of operation and design variables, including feed inlet diameter, feed inlet flow rate, feed solid concentration, apex diameter, vortex finder width, cylindrical diameter, cone angle, separation medium type, and inlet pressure [1]. The centrifugal energy within the different types of cyclones accelerates the size-based and/or density-based separation processes. Cyclones can be divided based on their mode of operation into hydrocyclones, dense medium cyclones, and water-only cyclones (Fig. 1). These cyclones are usually fixed vertically such as hydrocyclones and water-only cyclones, or inclined with 10-15° from horizontal such as a dense-medium cyclone. The separation medium is usually water in both hydrocyclones and water-only cyclones, while it is a medium of specific separating density in the dense medium cyclone. Also, a water-only cyclone has a wider cone angle than hydrocyclone and a dense medium cyclone [2]. In addition, there is a large overflow tube length in the case of a water-only cyclone, and the vortex finder width is usually larger in both water-only cyclones and dense medium cyclones than in the hydrocyclone.

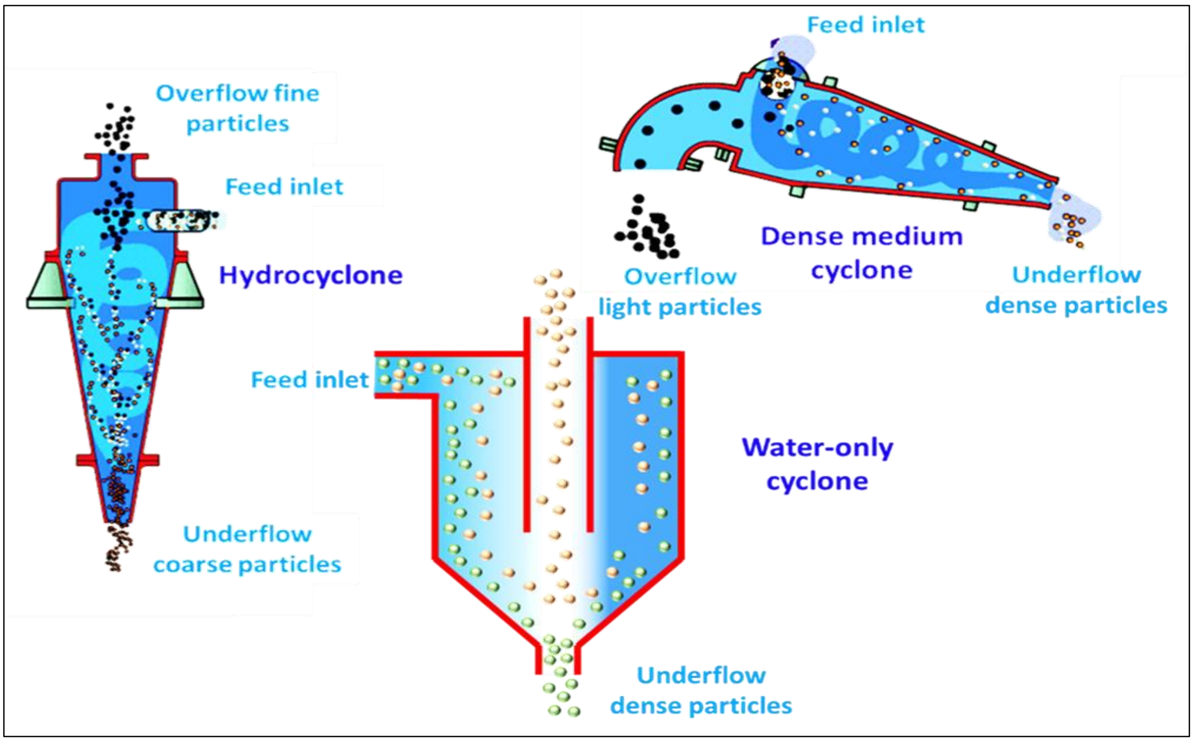

Fig. 1 Schematic illustration of different types of cyclone separators.

1.1. Hydrocyclone

1.1.1. Separation principle of hydrocyclone

Hydrocyclone is mainly employed for particles separation by size below 300 µm in mineral industries. The size-based separation in the hydrocyclone depends on the particle setting velocity to different particle sizes [1]. It comprises cylindrical and conical sections. The slurry of particles with different sizes is injected tangentially with high inlet pressure and a suitable volumetric flow rate to induce a centrifugal force, which speeds up the particle settling kinetic. This centrifugal force increases by decreasing the conical width of the cyclone. Within the cyclone, the solid particles influenced by drag, centrifugal, and buoyancy forces move in trajectories based on their sizes. Consequently, the coarse particles move downwards along the outer bed layer to the underflow through the apex, while the fine particles tend to migrate upwards near the central axial to exit to the overflow vortex finder (Fig. 2). The cyclone cone angle affects the particles retention time and in consequence, the separation quality, while apex width relative to the vortex finder width controls the amount of slurry reporting to the overflow. The typical amount of medium exiting the vortex finder is about 65% of the total medium inlet of the cyclone [1].

1.1.2. Current development in hydrocyclone

Recently, hydrocyclones have grown extra attention not only in minerals separation industries, but also in pharmaceutical, chemical, and petroleum for particle sizing and multiple-phase separation [3]. Freshly, various geometric assemblies of hydrocyclone designed with flat bottoms of different widths have shown a significant influence on minimizing fine particles by-pass to the underflow stream, but the excessive width causes by-pass of coarse particles to overflow stream [4].

In addition, more designs of hydrocyclones such as cylindrical-conical (CC), cylindrical-conical-flat bottom (CCB), cylindrical-conical-cylindrical bottom (CCC), multi-stage cylindrical (MS), and cylindrical (C) hydrocyclones have been introduced to improve the separation performance by eliminating the particle misplacement defect in conventional hydrocyclones.

Among these types, MS and CCC types have the lowest imperfection value and, in consequence, the highest separation performance with a cut size of 76 µm, while CC and C types have the lowest and largest cut size of 62 µm and 120 µm respectively. Besides, C and CCB have the lowest separation performance due to producing large turbulence [5].

In addition, the conical angle in the range from 3° to 28° at a varied cylindrical length-to-diameter ratio has a stronger effect than that at fixed cylindrical length on the separation efficiency [6]. Besides, high separation effectiveness is obtained by reducing the apex-to-vortex ratio [7].

Recently, modified designs of adding thin concentric rings to both the cylindrical and conical sections reduce the fine by-pass to underflow with additional improvement in separation keenness of separation at smaller cut [8].

1.1.3. Recent Industrial applications of hydrocyclone

In recent years, hydrocyclones have gained high attention due to their irreplaceable advantages in particle separation with a cut size of larger than 2 µm for feed size below 1 mm [9]. The high separation efficiency of hydrocyclones is achieved when conducted to feed particles with size in the range of 400 µm to 5 µm [10]. Furthermore, hydrocyclones (Fig. 3) have been extensively utilized in many industrial sectors such as mineral, coal, chemical, petrochemical, petroleum, textiles, papermaking, food, environmental protection, water treatment, soil remediation, waste management, agriculture, biotechnology, and nanotechnology [9, 11] Click or tap here to enter text.. The increased interest in hydrocyclones is attributed to the operation and maintenance simplicity with no moving parts, high separation efficiency, low energy consumption, small volume, and wide operation range [9, 12].

1.2. Water-only cyclone

1.2.1. Separation principle of water-only cyclone

Water-only cyclone is an enhanced density-based separator of autogenous medium for feed particle size finer than 1000 µm [13]. Compared to hydrocyclone, water-only cyclones are shorter with a limited conical section of a wide cone angle. The density-based segregation of the particles is accomplished by hindered settling environment in the upper section (cylindrical section) combined with the centrifugal force for enhanced kinetics. Thus, the dense particles move downwards along the wall into the underflow apex, while the light particles migrate near the center upwards to the overflow vortex finder as displayed in Fig. 4.

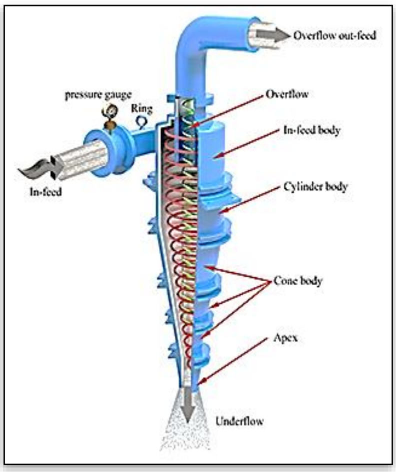

Fig. 2 Schematic illustration of hydrocyclone size separator.

Fig. 3 Typical industrial-scale hydrocyclones.

It has several advantages including a simple structure with no moving sections, low capital/production cost, occupying small space, low maintenance cost, no external feed medium, no costly chemicals, and low environmental pollution. Furthermore, the water-only cyclone is a unique choice whenever low washing cost is preferred over high separation performance [14].

1.2.2. Current development in water-only cyclone

Recently, a two-stage water-only cyclone was characterized and numerically simulated on super clean coal production. It comprises a concentrated cylindrical section as the first stage and a large cone angle cyclone as the second stage as illustrated in Fig. 5 [15]. The benefit of the first stage is preventing the by-pass of coarse particles to the overflow stream which ensures the separation of fine particles and mud to the overflow stream, while the second stage is utilized in separating the dense particles from lower-density particles [15]. This modern modification in coal upgrading removed a large amount of high ash mud in the first stage cyclone, which eliminated the wide size negative effect on the density-based separation in the second stage cyclone [15].

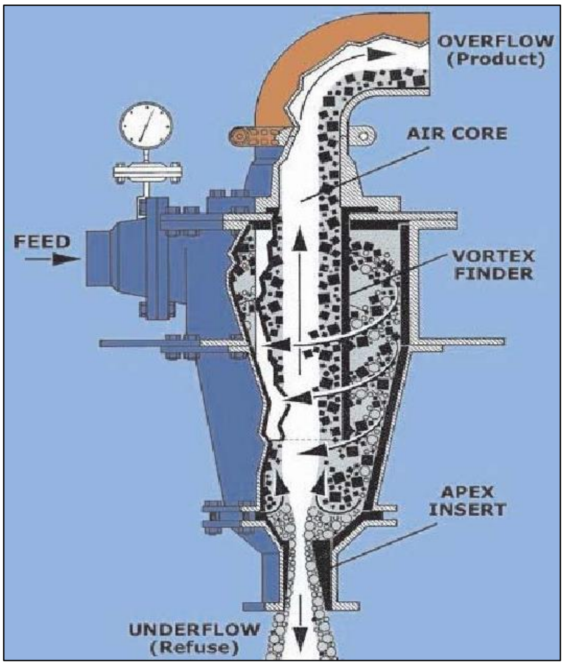

Fig. 4 Schematic illustration of a water-only cyclone density separator.

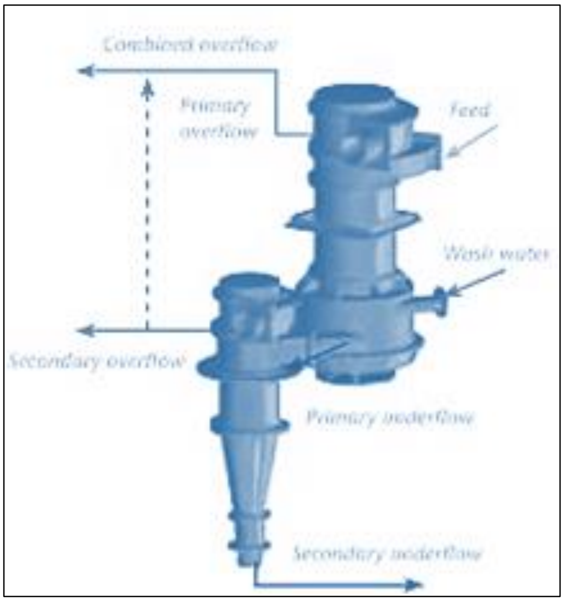

Fig. 5 Schematic diagram of a two-stage water-only cyclone.

Another way to enhance the separation effectiveness has been achieved by developing a three-stage cone water-only cyclone, which reduces the by-pass of dense particles to overflow by creating a larger axial and tangential velocities gradient compared with a single-stage water-only cyclone [2, 16].

A more advanced development for water-only cyclones has been established recently [17]. The slurry feed is injected tangentially to the fluidized separation cylinder of the fluidized water-only cyclone, producing a centrifugal force to accelerate the settling of particles into the cylinder concentrating rings. The inlet fluidizing water pressure loses and stratifies the particles based on density differences, where the dense particles flow out of the fluidization holes to be collected in the condensing cone to the underflow stream, while the light particles are continuously flowing into the overflow stream [17]. The modified separator provided a significant solution for continuously enhanced gravity separation of dense minerals, for example, it concentrated a mixture of hematite and quartz from 30% Fe to 56.5% with sufficient recovery [17].

Recent Industrial applications of water-only cyclone

In the past, water-only cyclones have been used for concentrating – 600 µm ores. In recent years, they are applied to treat the intermediate particle sizes and to increase their separation effectiveness.

Recently, a water-only cyclone was employed to treat chromite fines from a low-grade plant tailing stream containing 22.5% Cr_2O_3, 23.1% Fe(T), and 39.3% SiO_2, producing an underflow stream assaying 39.3% Cr_2O_3, 17.9% Fe(T), 10.9% SiO_2 [18].

In Turkey, a modified water-only cyclone fixed with an inclined angle with 20 t/h capacity of 200 µm coal has been employed as an alternative to flotation and spiral concentrators at the Karbomet plant [13].

1.3. Dense-medium cyclone

1.3.1. Separation principle of dense medium cyclone

A dense medium cyclone is mainly employed for sharp particle size separation in the range of 150 mm to 0.5 mm based on density differences in a separating medium. The separation medium is usually formed by mixing fine magnetite particles with water to allow precise control of medium density, and the dense medium cyclone is usually fixed at a 10-15° angle from horizontal as illustrated in Fig. 6 to prevent the gravitational force from slumping the dense medium toward the apex, which pinches the required air core. Similar to hydrocyclone, an air core is required through the central section of the cyclone to ensure proper directional migration of the inner medium toward the vortex finder. Within the cyclones, the feed slurry and separating medium are injected tangentially into the side of the cyclone and spins creating a vortex. Thus, the particles are subjected to two opposing forces; a centrifugal force pushing the dense particles to migrate toward the wall, and a drag force causing the particles to move toward the axis.

1.3.2. Current development in dense medium cyclone

Recently, the application of computational fluid dynamics has been usefully employed extensively to simulate hydrodynamic force, three-phase flow, magnetite segregation, medium-to-coal ration effect, fine particles separation, improved design, and performance evaluation in the dense medium cyclone [19, 20] Nowadays, a dense medium cyclone is used to concentrate the vast majority of coal fed to the preparation plants.

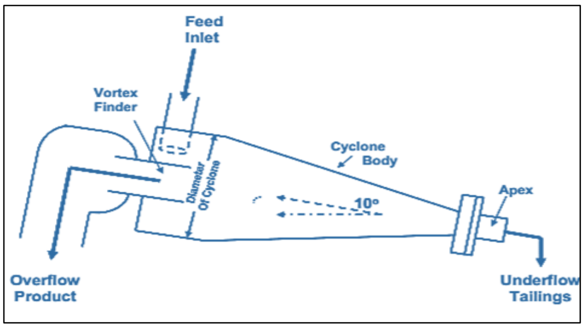

Fig. 6 Schematic illustration of a dense medium cyclone.

1.3.3. Recent Industrial applications of dense medium cyclone

Dense medium cyclone has been widely employed for the concentration and pre-concentration of metalliferous, iron ore, diamond, and industrial minerals [21]. Recently, an industrial scale dense medium cyclone of 250 t/h capacity for coal preparation has been operated by Ingwenya mineral processing plant located at Clewer, Emalahleni, South Africa, which produces 120,000 tons per month of high-grade coal Fig. 7. In addition, a dense medium cyclone has been recently installed for pre-concentration of metalliferous at Glencore's McArthur River mine in Australia's Northern Territory [21].

Fig. 7 Industrial-scale dense medium cyclone in South Africa.

2. Recent trends in wet separation technologies

Technologies of density-based separation have been employed noticeably in the early historical time and lately to process various minerals. These technologies exploit the density differences of various particles within the ores to concentrate and recover valuable minerals. The different technologies and techniques that employ the aspect of density separation are divided into dry and wet separation technologies.

Fine and ultrafine grinding of finely disseminated ores is mandatory to free valuable minerals from gangue minerals. The conventional density-based processing associated with these kinds of ores is usually ineffective. Recently, enhanced wet density-based separation machineries were developed to be applied in fine and ultrafine particle separation. These technologies showed the significant capability to upgrade different kinds of minerals such as gold, copper, platinum, tantalum, tungsten, bentonite, iron, chromite, coal, magnesite, colemanite, wolframite, rare earth minerals, oil sand, celestite, etc. The enhanced density-based separation is a separation process, which employs centrifugation to recover the fine/ultrafine valuable minerals from the gangue minerals, based on the density differences. The centrifugal force produces a force larger than the gravitational force [22]. Some of the major enhanced gravity separation technologies are shown in Fig. 8. It also shows the separation mechanism of the different enhanced separation technologies.

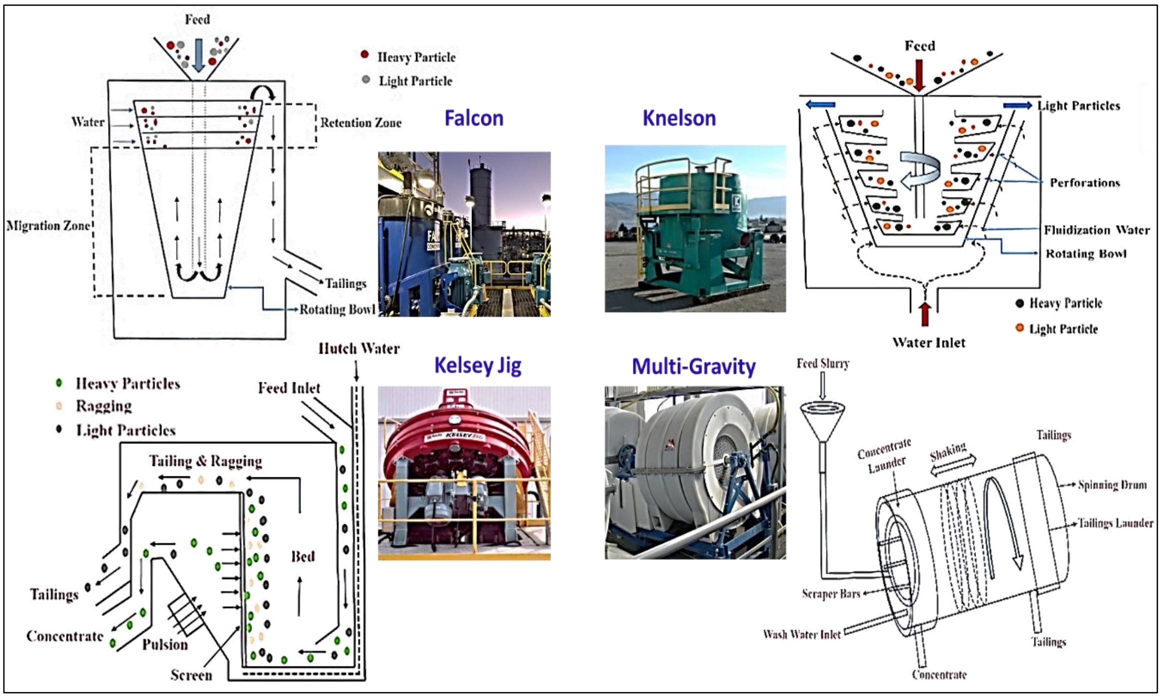

Fig. 8 Illustration of major enhanced density-based wet separation technologies [22].

2.1. Falcon concentrator

2.1.1. Separation principle of Falcon concentrator

Falcon concentrator, as an enhanced density-based separation technology shown in Fig. 9 is based on the flowing film phenomenon, in which the feed entering the separator acts like a flowing film in a high revolving bowl that enhances the differential settling velocities of different particles. During the separation process, the feed-in is injected toward the bottom of the separator bowl at the segregation zone, and the applied centrifugation forces the feed particles of higher density to be trapped inside the separation retention zone, while the lower density particles report to the outlet. Furthermore, the dense particles usually remain in the bottom grooves, and the medium-dense particles settle at the top grooves as a result of the greater radial velocity of fluidized water in the top grooves than that in the bottom grooves [23]. In the Falcon separator, the bed stratification on the bowl wall takes place as a result of the variance in settling velocity against fluidization water flowing through holes in the bowl grooves [22].

2.1.2. Current development in Falcon concentrator

During the recent development, the application of Falcon concentrator extended to separate not only gold particles but also other industrial minerals. It was also applied in the recovering valuable materials from spent dry batteries [24]. In addition, the distribution, migration, enrichment, and numerical simulation of the particles of different densities besides operation parameters were investigated recently, unlike the preceding studies that focus on the final separation streams [23, 25-28].

Fig. 9 Falcon separator.

The extremely high centrifugal energy of up to 300 g's, which can also reach 600 g's in some recent types, makes Falcon concentrator a unique technology that can separate particles at a separation density lower than that of the other enhanced density-based separation technologies. Falcon concentrator has the capability to upgrade particles of sizes finer than 25 µm (dense particles) and 75 µm (lower density particles) [22].

Falcon separator has three main design series known as semi-batch (SB), continuous-gravity (C), and ultrafine (UF) series (Fig. 10). In the SB type, the slurry is continuously injected and the higher density particles are collected in the retention zone by injecting fluidized water pressure through annular grooves to adjust retention capacity and avoid compaction. Whereas the C type runs continuously without additional water, where hoppers with air-operated valves control the flow in the retention zone. The UF type is designed with a smooth bowl with a reduced diameter at the overflow outlet without using countercurrent water pressure that may flush ultrafine dense particles to the wrong stream. The UF type is capable of treating particles finer than 3 µm with an enhanced gravitational force reaching 600 g's [22], while SB and C series can provide up to 300 g's [29, 30]. Both SB and UF types should be turned off prior to saturation to avoid the loss of dense particles [25].

2.1.3. Recent Industrial applications of Falcon concentrator

SB, C, and UF types of Falcon concentrators exist industrially. For instance, the UF type has been magnificently employed to efficiently recover ultrafine particles (-3 µm) of native metals such as silver and gold as well as metal-bearing heavy minerals such as tantalum, tungsten, tin, cobalt, and chrome [25].

2.2. Knelson concentrator

2.2.1. Separation principle of Knelson concentrator

The operation principle is approximately similar to that of Falcon concentrators, which exploits the differential settling velocity of particles in a centrifugal field under the influence of fluidization water flow velocity [31]. Knelson concentrator is more favorable in mineral industries attributable to its low cost, small environmental influence, and its capability of upgrading a wide feed size from 850 µm to 20 µm by optimizing the enhanced gravitational force and the pressure of fluidized water [32]. In most applications, the common optimum enhanced gravitational energy of the Knelson concentrator is in the range of 60 and 100 g's, reaching to 180 g's [22]. Knelson concentrator was primarily a semi-batch system for gold concentration [22]. Recently, the Knelson concentrator was modified as a Continuous Variable Discharge (CVD) separator for upgrading other kinds of ores such as magnetite, chromite, cassiterite, coal, colemanite, pentlandite, tantalum bearing minerals, heavy mineral sands, and rare earth minerals [33]. During the operation process of the Knelson concentrator, the feed slurry entering at the lower section of the spinning bowl moves under the centrifugal force toward the bowl wall at different settling velocities depending on the size and/or density of the particles. Besides, the fluidization water is injected tangentially at a high pressure in an opposite direction to the centrifugation process to crease a fluidization concentrate bed. It is worth mentioning that the fluidization water showed enter the bowl with high pressure to prevent the severe compaction of dense particles owing to the high centrifugation process [34]. Furthermore, two distinct zones are formed in the radial direction known as dilute and separation zones. The light fine particles of gangue minerals tend to form the dilution zone then move to the overflow out of the spinning bowl. While the dense particles displace the lower density particles and in consequence settle in the separation zone as a concentrate toward the concentrate bed in semi-batch version or to the concentrate stream in the CVD type of Knelson concentrators.

2.2.2. Current development in Knelson concentrator

Recently, fundamental simulation and modeling studies for Knelson concentrators were carried out to fully understand the mechanisms of operation using Computational Fluid Dynamics (CFD) and Discrete Element Methods (DEM) [35-37]. The DEM simulation was also validated with the laboratory experimental results which proved that the bottom and the lower bowl rings in compared with the upper ones are filled with magnetite particles at the end of the separation process. While silica particles are reported to the surface of the concentration bed at the upper rings [37]. Previously, tungsten particles from a synthetic sample were accumulated at both the lower rings and the lower section of the bowl, which confirms the recent DEM simulation findings [38].

The presence of clay particles negatively impacts the performance of some separation operations. In the contrast, it was found recently that clay particles report to the tailing stream without affecting the concentrate bed which in consequence insignificantly affects the efficiency of the Knelson separator [39]. One of the recent developments of Knelson separator was its utilization as a dry separation technology by replacing fluidizing water with fluidizing air, which removed the use of a huge volume of water and eliminated the issues associated with the handling of process waste-water [34, 40]. The unit was also designed for pneumatic fluidization by controlling the air fluidizing pressure into the inner bowl in addition to the use of air lances to remove the solids into the tailings sealed pail [34, 40]. In addition, the modeling and optimization on different particles sizes have been done to clearly understand the separation mechanism of the modified process, which showed different optimum conditions depending on the feed particle size [41].

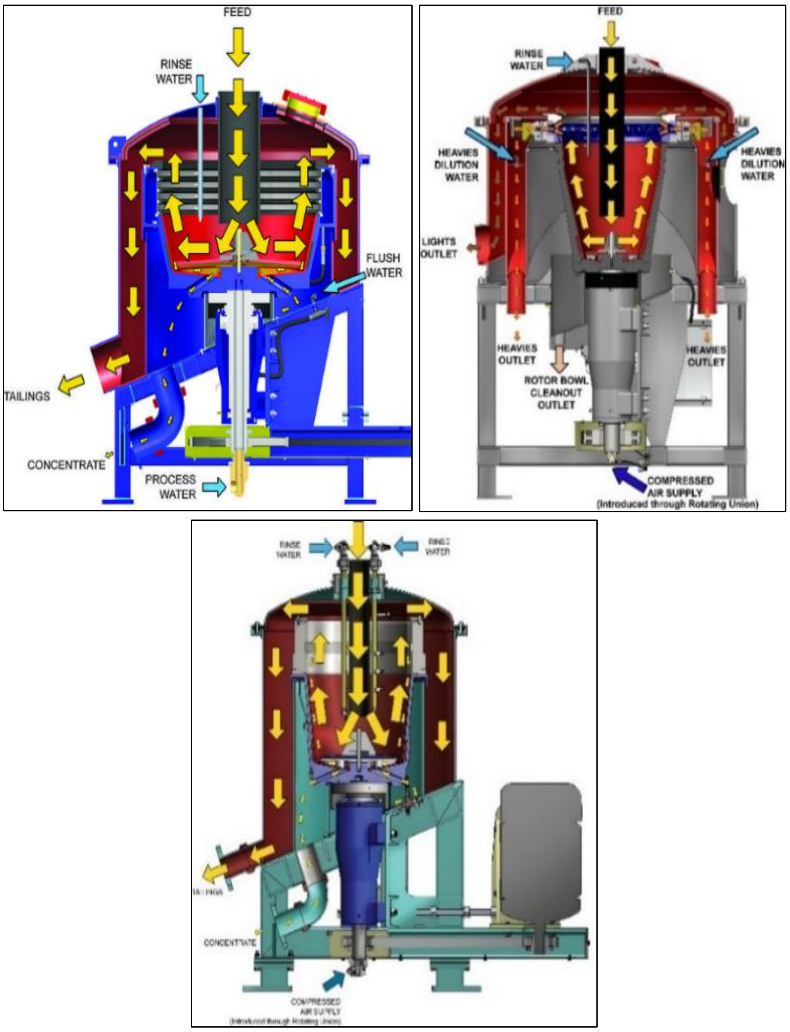

Fig. 10 Semi-batch, continuous, and ultrafine series of Falcon concentrators

2.2.3. Recent Industrial applications of Knelson concentrator

Knelson concentrator has been successfully employed in the industry to recover gold, and recent studies showed the capability of Knelson concentrator to recover tantalum, niobium, tin, chromite, rare earth minerals, etc. [42]. Furthermore, the Knelson concentrator (Fig. 11) was utilized in the industry to maximize the fine coal quality and to scavenge valuable metals like gold from flotation tailings [43]. Besides, a semi-industrial scale was carried out to recover tantalum and niobium effectively [44]. In addition, the Knelson separator was used at many gold mines in Australia, Russia, China, Canada, South Africa, Peru, Spain, the USA, and Malaysia. For instance, at Rio Nacea gold-copper mine in Spain, the Knelson concentrator replaced the jig unit in the jig-flotation-cyanidation circuit which improved the gold recovery from the gravity process from 2% to 25% with monthly net profitability of about $150,000 [42].

Fig. 11 Industrial Knelson Concentrator installed at Asanko Gold in Ghana.

2.3. Kelsey jig

2.3.1. Separation principle of Kelsey jig

Kelsey jig is a recent version of a traditional jig utilizing the centrifugal force of up to 100 g's to effectively separate near-gravity fine/ultrafine particles of sizes from 5 µm to 500 µm [45]. Its separation effectiveness by stratification to films of different densities depends mainly on the particle bed thickness over the cylindrical co-axially spinning screen and the velocity profile of fluidization water through the spinning screen with a certain pulsation rate. After bed stratification over the screen, the dense particles migrate through the ragging bed and screen opening to the concentrate launder, while the light particles flow over the ragging bed to the overflow as tailings [22].

2.3.2. Current development in Kelsey jig

Recently, Kelsey jig was successfully conducted to recover a variety of valuable minerals for different kinds of ores such as iron, sands, coal, manganese, nickel, gold, tin, platinum, tungsten, chromite, and scheelite [22] For example, Kelsey jig was used as a scavenger and a cleaner for tin gravity separation tailing and shaking table concentrate respectively, which replaced the leaching and flotation processes for environmental safety and for eliminating collector reagent requirements with maintaining the plant recovery of improved product quality [46].

2.3.3. Recent Industrial applications of Kelsey jig

In recent years, Kelsey jig has been considered a better option for fine and ultrafine beneficiation processing. Its application was limited in the coal and mineral industries due to the lack of skills of the operators, the equipment's mechanical complexity, and the high volume of water necessities [22]. However, the Kelsey jig is a promising technology due to its high production capacity and quipping less plant area (Fig. 12) [45].

2.4. Multi-gravity separator

2.4.1. Separation principle of multi-gravity separator

The multi-gravity separator employs an enhanced spiral and shaking table mechanism inside a spinning inclined drum, which promotes the separation of fine/ultrafine particles of different densities with a particle size range from 150 µm to 5 µm. During the separation process, the feed pulp and wash water are continuously injected into the middle of the drum internal surface. Then slurry flows in spiraling directions inside the spinning drum, and the acceleration with the drum rotation forces higher density particles pinned to the drum surface to travel uphill with the shaking direction using the assistance of scrapers to the outer wall of the drum existing from the upper side of the drum. While the less dense particles move with the medium (wash water) downhill through the drum length to the drum bottom as demonstrated in Fig. 13 [47].

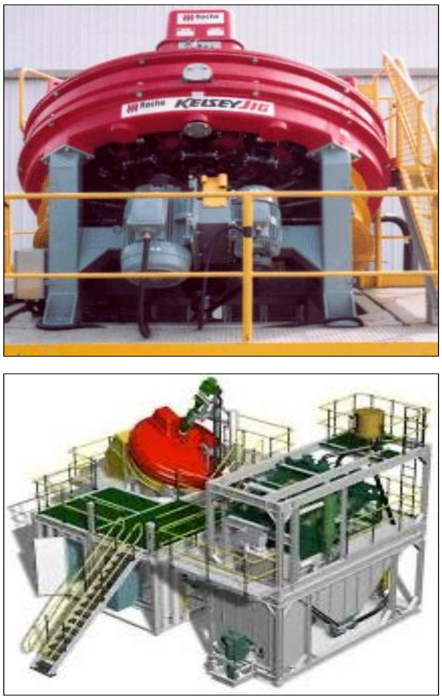

Fig. 12 Industrial-scale Kelsey jig.

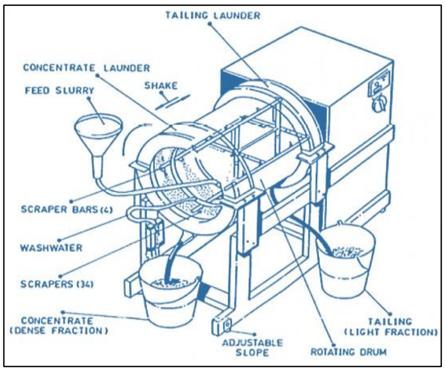

Fig. 13 Schematic illustration of a Mozley multi gravity separator [47, 48].

2.4.2. Current development in multi-gravity separator

Some typical applications are recovering precious metals from alluvial ores; and oxide minerals, sulfide minerals, uranium, etc. from primary ores. It has also been utilized for pre-concentrating heavy mineral sands or industrial minerals like anatase, barytes, chromite, coal, etc. Besides, its application in scavenging precious metals and valuable minerals from tailings and slime streams [49].

2.4.3. Recent Industrial applications of multi-gravity separator

The interest in enhanced density-based separators was revealed after the tremendous success of multi-gravity separators in the chromite industries in Turkey [50]. Based on plant necessities, a multi-gravity separator (Fig. 14) is utilized as a rougher, scavenger, or cleaner in the mineral processing industries [22]. Recently, Extensive investigation has been performed to explore the applications of multi-gravity separators in diversified areas in the mineral industries [49, 51]. However, in coal industries, multi-gravity separator was insignificant in producing clean coal as a result of separating clay slims with clean coal particles to the product stream [22].

3. Recent trends in dry separation technologies

Dry separation technologies have gained more attention than wet technologies in recent years to avoid water consumption, slimes issues in water, solid dewatering problems, and water recycling necessities [52]. Thus, varieties of countries such as China, India, and Turkey have applied new rules to inspire the growth of dry separation technologies instead of wet separation ones [52]. The recent trends in the existing dry separation technologies and the associated basic principles have been thoroughly summarized, and the major dry density-based segregation technologies are shown in Fig. 15.

Fig. 14 Industrial-scale multi-gravity separator.

3.1. Air jig

3.1.1. Separation principle of air jig

The main operating principle of modern air jig comes from the separation mechanism of the wet jigging process, which exploits the difference in terminal velocities of different components within the ore by employing a deck vibrating force (to move the particles from the feed to the discharge) and a pulsed airflow (to enhance the stratification), while the continues airflow is used to loosen the particles bed on the deck [53, 54]. Furthermore, the ore on the air jig screen is loosened gradually and stratified into layers of lower density/finer size particles at the top and higher density/coarser size particles at the bottom. Then the layers are separated at the discharge end of the inclined vibrating deck as illustrated in Fig. 16. The air jigging operation follows similar steps as in the conventional wet jig; differential acceleration, hindered settling, and consolidation trickling [55].

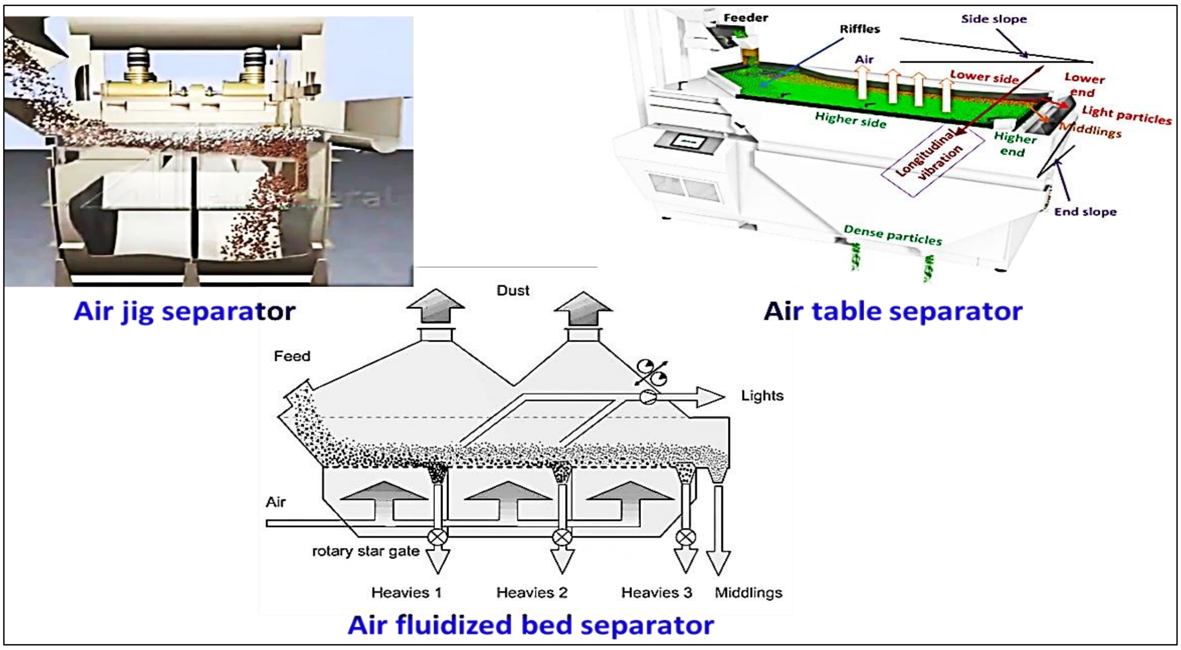

Fig. 15 Major dry density-based separation technologies.

3.1.2. Current development in air jig

Recent research studied the particle movement trajectory, which indicated that pulsating airflow regularly enlarges the differential trajectory of particles of dissimilar densities [54].

Generally, the air jig operation initiates the fluidization of ore particles under the pulsed airflow, and the minimum air velocity of fluidization is a key factor for designing the air jig technology. Thus, the new investigation studied the fluidization phenomena of the air jig [54], and found that the optimum minimum airflow and reinforcing the particle movement was obtained at the intermediate frequency region of 3-4 Hz pulsation frequency.

Researchers investigated air jig operation by analyzing the effects of different operating parameters such as ore characteristics, jig structural design, and separation efficiency. The analysis showed that the size ratio limit between higher and lower density particles should be less than 1:4 to eliminate the particle mixing which reduces the separation efficiency. The analysis indicated also that the optimum air velocity is 1202-1252 m/s with an optimum pulsating air frequency of 3-4 Hz [52, 56].

3.1.3. Recent Industrial applications of air jig

Air jigs can separate different size fractions smaller than 50 mm, and its capacity enlarges with coarse particle size ore. The ore surface moisture of less than 6% is also preferred regardless of the inherent moisture. For example, coal of 30% moisture or even more with less than 6% surface moisture can be efficiently upgraded using an air jig [55]. An air jig is efficient in separating particles of less than 10% of near-gravity particles at a density higher than 1.8, whereas a wet jig is more efficient for near-gravity materials higher than 10%. Recently, industrial upscaling of air jig technology was realized for coal preparation in the United States, Ukraine, Spain, India, and Colombia [55]. It was also built in Turkey [53]. A semi-industrial air jig of 300 kg/h capacity was developed in Germany to process coal samples from several countries such as Turkey, Brazil, and Germany. Whereas an industrial air jig of 50-120 t/h capacity was built in the United States [52].

3.2. Air table

3.2.1. Separation principle of air table

Similarly, to air jig, the air table consists of a vibrating mesh deck with airflow from the bottom to loosen the particle bed to be stratified based on the settling velocity of particles with different densities in addition to the frictional resistance with the vibrating deck surface [57]. The air table uses a vibrating motion similar to a wet version, and the dry feed is injected at one of the corners of the deck. The air table generally comprises a riffled top deck mounted on an air compressor, which moves the higher density particles to move upslope due to the movement of the table, and the lower density particles move downslope along the short route as illustrated in Fig. 17.

A new version of the air table known as densimetric table was established recently. Its separation mechanism is exactly similar to the air table as shown in Fig. 18. In the densimetric separator which employs vibration force and air blowing effect, the feed particles are introduced through the upper part by a special hopper. Then the feed is spread on the entire surface, and the controlled air pressure on the particles bed provides high-efficient separation performance. In addition, the vibration of the inclined table screen pushes the higher density particles towards the top, whereas the lower density particles slide towards the hopper bottom that collects the light particles. The table mesh size is always chosen based on the feed characteristics to prevent the particles from passing through the screen. The densimetric table was initially designed to handle 0.5 to 3 t/h of ore.

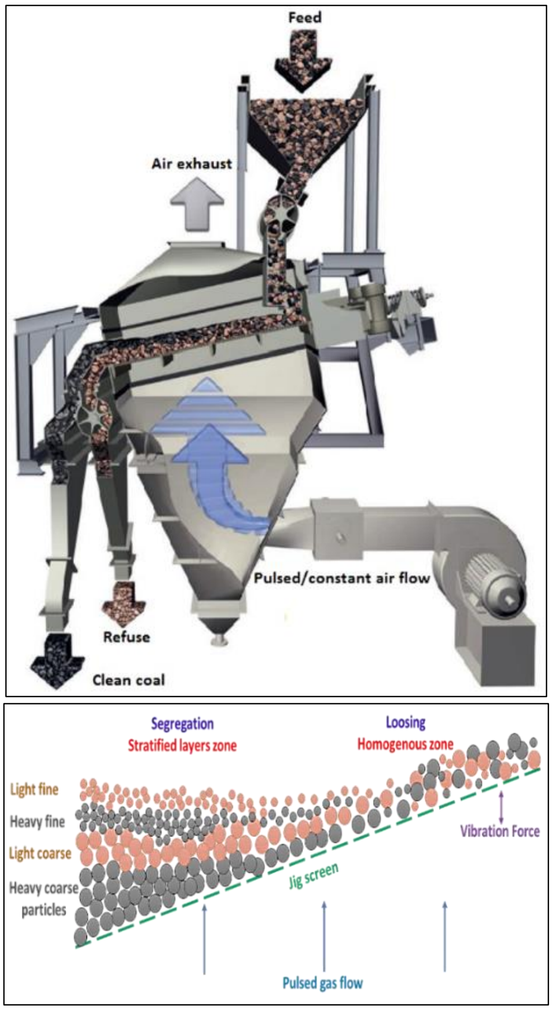

Fig. 16 Schematic illustration and the mechanism of separation using air jig technology.

3.2.2. Current development in air table

Recently, more efforts have been occurred to enhance the separation efficiency by optimizing the air table design especially by improving the vibration force, table surface, and baffles. This led to the developing of new designs like the KAT air table separator (Fig. 19), FGX compound dry separator (Fig. 20), and FX air table separator (Fig. 21). The KAT was industrialized by the Korea institute of geoscience and mineral resources, while both FGX compound dry and FX air table separators were developed by the Chinese research department [52].

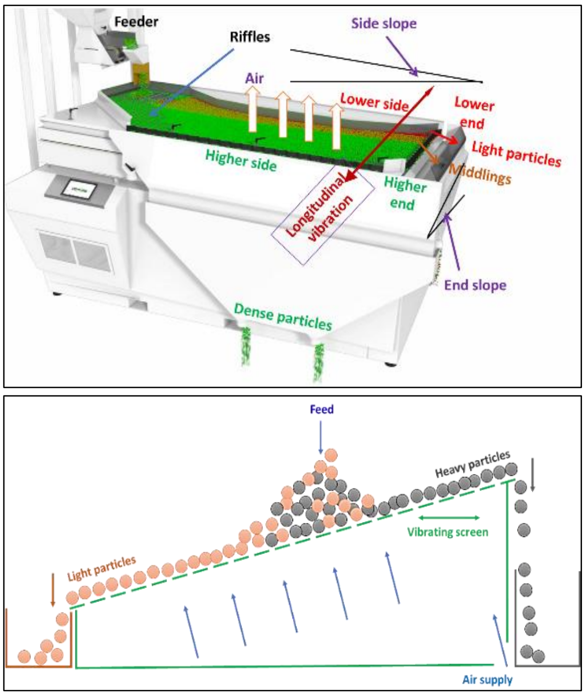

Fig. 17 Mechanism of separation using air table technology.

In the KAT air table separator, the different air drags and friction forces segregate the lower density particles to accommodate at the bed lower bottom, while the higher density particles tend to accommodate on the upper layer of the bed as demonstrated in Fig. 19. Then the different density particles are discharged into regions by a number of splitters.

While in FGX and FX separators, the vibration force are provided by the suspension vibration motor and crank link vibration motor respectively. In these two kinds of modern separators, the dry ore is continuously fed on the table surface to achieve particle segregation as a result of different drag forces, buoyancy, and surface friction force. The baffles are also used to enhance the migration of the higher density particles upwards which strengthens the separation efficiency.

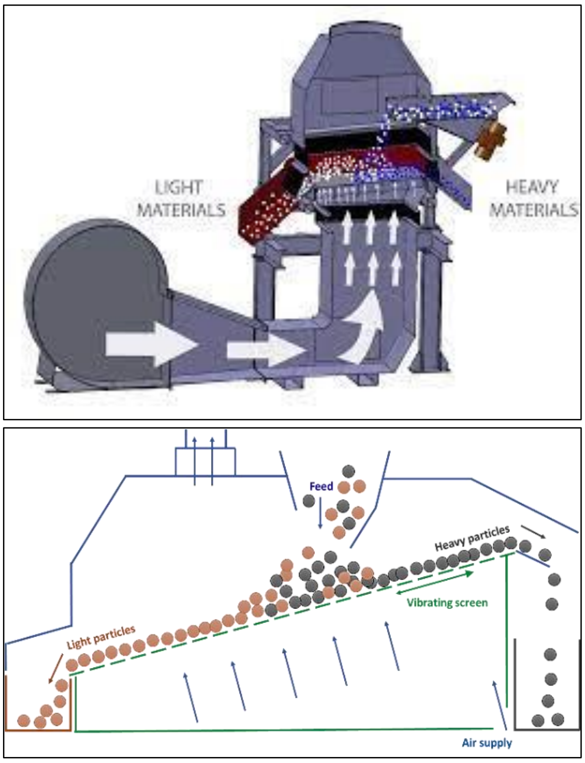

Fig. 18. Densimetric table separator and its separation mechanism.

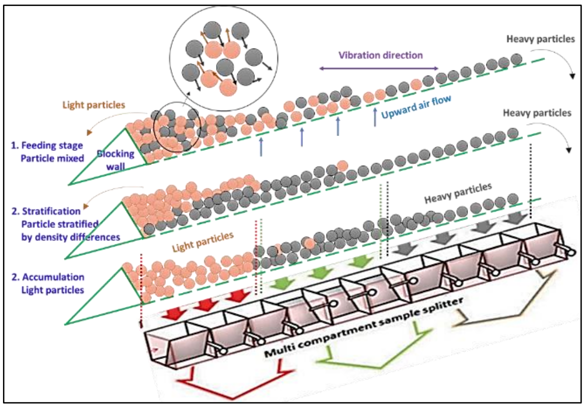

Fig. 19 Schematic illustration of KAT air shaking table separation mechanism [58].

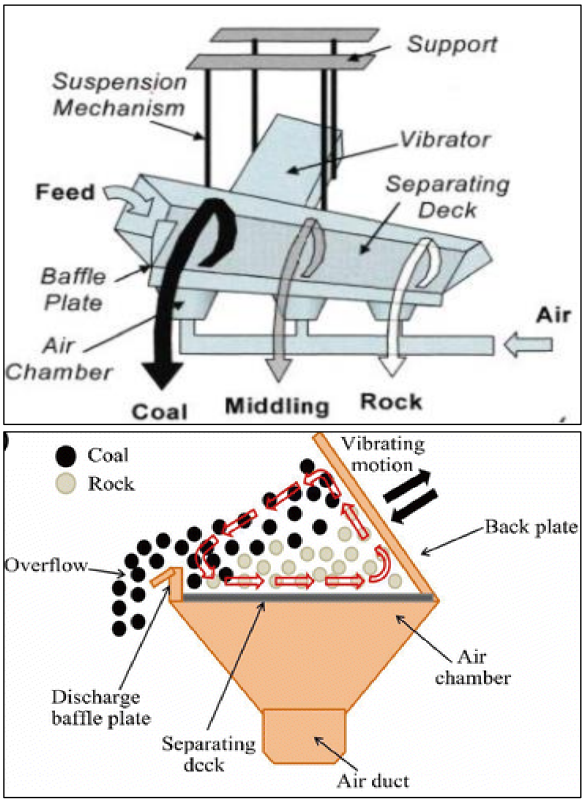

Fig. 20 FGX dry separator and its separation mechanism.

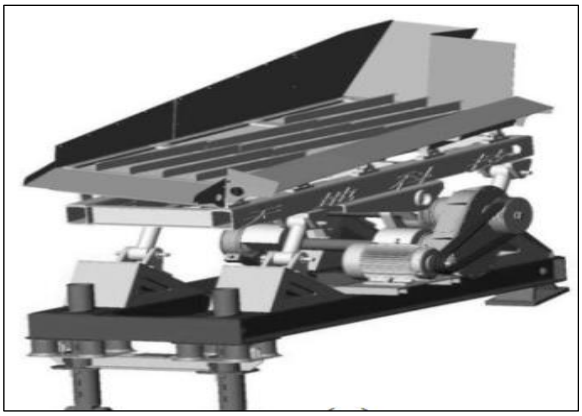

Fig. 21 FX air table separator.

3.2.3. Recent Industrial applications of air table

Air table can separate different size fractions smaller than 80 mm but larger than 6 mm. Recently, an industrial scale of densimetric table separator, KAT air table separator, and FGX compound dry separator have been constructed. The industrial FGX had a 100 t/h capacity [58]. The semi-industrial scale of the FGX unit verified the capability to efficiently upgrade coarse coal particles with a combustible recovering of about 90% and a rejecting of almost 80% ash. Furthermore, over 800 units were successfully in operation in China, Indonesia, Mongolia, North Korea, South Africa, Philippines, Ukraine, United States, and Vietnam [59].

3.3. Air fluidized bed separator

3.3.1. Separation principle of air fluidized bed separator

The air-fluidized bed uses a pseudo-fluid with a constant bed density to separate the feed particles into dense (sink) and light (float) products. There are three initial designs of fluidized bed separators [60]:

1. Frazer and Yancey separator.
2. Tilted bed separator and sluice box established by Warren Spring Laboratories.
3. Rectangular trough separator and circular trough separator.

Recently, air fluidized bed separators can be categorized into different types based on the external forces employed for efficient separation performance as shown in Fig. 22; vibration, pushed air flow, and magnetic field external forces; or without any external force (i.e., the normal type). During the separation process, a dense medium made of magnetite powder (-0.3 + 0.15 mm) and coal particles (-1 mm) is fluidized with compressed air flow, forming a pseudo separation medium. Then once the ore particles enter the fluidized bed, the lower density particles float and the higher density particles sink at the surface and bottom of the bed respectively [61]. The detailed mechanism of air fluidized bed separator used for example to upgrade coal ore is shown in Fig. 22. Fig. 22 shows the bed before and after fluidization by conducting compressed air, and the separation of coal ore after feeding it to the fluidized bed into clean coal particles at the top and ash particles at the bottom of the fluidized bed [61].

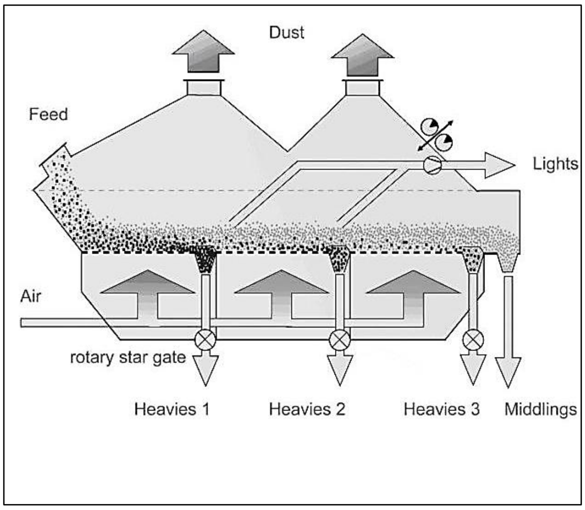

Fig. 22 Schematic illustration of air fluidized bed separators.

3.3.2. Current development in air fluidized bed separator

For normal air fluidized bed separators, it was not efficient to upgrade coal ore of grain size smaller than 6 mm due to the instability of the bed as a result of the formation of high bubble phase.

Thus recently, more efforts were carried out to achieve high separation performance by introducing external energy such as vibration energy, pulsed airflow, and magnetic field. The particle fluidization performance is enhanced by applying external vibration energy that cut and minimizes the formation and growth of big bubbles that reduce the stability of the bed density [62, 63] Thus, recently, a counter-current vibrated fluidized bed separator has been developed, and the separation medium was -0.355 + 0.125 mm sand powder. The device overcome the establishment of large bubbles and enhanced the bed density stability. Thus, the device in a semi-pilot scale was efficiently used to upgrade – 6.35 + 1 mm and – 6 + 0.5 mm coal ore [52].

As another method to produce a magnetically stable fluidized beds, a magnetic force was introduced into an air fluidized bed separator. The magnetic force improves the fluidization performance for efficient separation of –6 mm coal by minimizing the bubble phase in the fluidized bed as a result of arranging the magnetite particles along the magnetic field lines forming stable bed density. This caused an efficient separation for -6 + 3 mm, -3 + 1 mm, and -1 + 0.5 mm coal ore [64, 65].

A pulsed air fluidized bed was also introduced for efficient bed fluidization with uniform distribution of bed density as a result of defeating the bubble growth in the fluidized bed. Thus, the separation performance of -6 + 3 mm and -3 + 1 mm coal was high using pulsed air fluidized beds [66-69].

Iron ore in recent years was also upgraded using an air fluidized bed separator to reject gangue minerals. The used binary dense medium consisted of low-density zircon and iron powder for separation of -31 + 6 mm coarse iron ore. This led to a satisfactory separation performance which has an important potential in the iron industry [70].

3.3.3. Recent Industrial applications of air-fluidized bed separator

Recently, air fluidized bed is one of the recent trends in air coal preparation in many countries such as Australia, Canada, South Africa, China, India, Japan, etc. [52].

The first industrial novel air fluidized bed separator of 50 t/h capacity for coal preparation plant was built at the Xinjiang Energy Co., LTC., of the Shenhua Group [61]. The device comprised of coal separation, medium recovery, air supply, and duct collection on the same stand. The fluidized bed consisted of fine magnetite and coal with a separation density in the range between 1.3 g/cm^3 and 2.2 g/cm^3 by controlling the amount of fine coal in the binary medium, which is beneficial in separating different quality coal ore [61].

The semi-industrial air fluidized bed separator effectively reduces the ash and sulfur contents of coal ore, but it is noticed that the separation performance is significantly affected by the increased amount of moisture contents [52].

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