Beyond Bessemer: the past, present, and future of dense medium separation in the coal industry

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Abstract. This paper traces the development and evolution of dense medium separation (DMS) equipment in the coal industry, beginning with Sir Henry Bessemer's 1858 patent. It chronicles the progression from early conceptual designs to advanced systems used in modern coal processing plants globally. The study examines both static baths, such as WEMCO drums, Drewboy separators, and Norvalt baths, and dynamic separators like the Dynawhirlpool, Larcodems, TriFlo separators, Three-product cyclones, and DMS cyclones, highlighting innovations that enhanced operational efficiency, feed capacities, and performance. A particular focus is placed on the South African coal industry, which has played a pivotal role in advancing DMS technology through local engineering ingenuity and adaptation. The paper also reviews the current state-of-the-art in DMS technology, discussing recent advancements and emerging trends, while considering future challenges and opportunities as the coal industry evolves. By celebrating historical milestones, recognizing key contributors, and inspiring future innovation, this work honours Sir Henry Bessemer's legacy and underscores the importance of continued progress in DMS technology for a more efficient and sustainable coal industry.

1 Introduction

Coal mining dates back thousands of years with the earliest records pointing to ancient China, the Roman empire and other historical economies. [1,2,3]. Coal was primarily used for heating, but with the invention of James Watt's steam engine in the late 1700's and the rise of the Industrial Revolution, coal was used for more than just fuelling the ovens of blacksmiths and artisans [4]. Coal fired steam engines were initially used to pump water from coal mines [5].

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Fig. 1: James Watt's original steam engine, an invention that would change the face of the world, designed in 1769 and improved in 1774 [6]

Coal is heterogeneous by nature, and consists of carbonaceous, volatile, and mineral matter and therefore beneficiation of the raw coal ore is required to upgrade the coal quality to be fit for purpose. The following gives an overview of early technologies and the development that took place to evolve the industry to modern dense medium separation technologies and practices.

2 Development of coal beneficiation technologies

Until shortly before the Industrial Revolution, coal made a negligible contribution to global energy consumption. The following graph highlights the exponential growth seen in coal being used as an energy source in England and Wales from the 18th century onwards [5]:

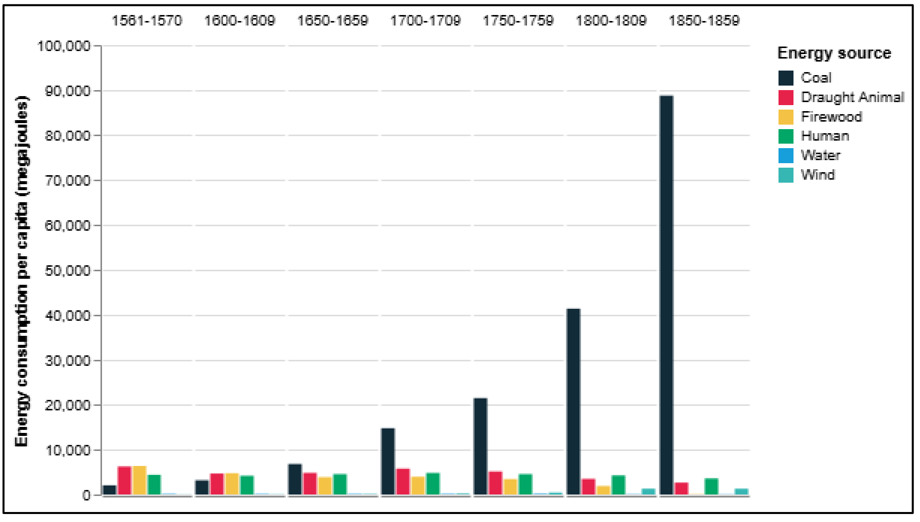

Fig. 2: Annual energy consumption per head [MJ] in England and Wales, 1561-1859 [5]

Initially, the need for coal beneficiation was to get to a more efficient and consistent energy source by removing shale, rocks, and other non-combustible matter. The need for consistent, high-quality coal increased as coal became a primary fuel source for industrialization and power generation. These were the ideal conditions to motivate innovative developments and inventions to better the then-current coal handling and washing processes.

2.1 Handpicking

In the early days of coal beneficiation, the process relied heavily on handpicking, where workers would stand next to a table or slow-moving belt and physically remove the obvious "non-coal" particles. These rocks / shale / impurities were then discarded into a chute or separate area. The following photograph of an American colliery depicts the typical working conditions of the late 19th centuary.

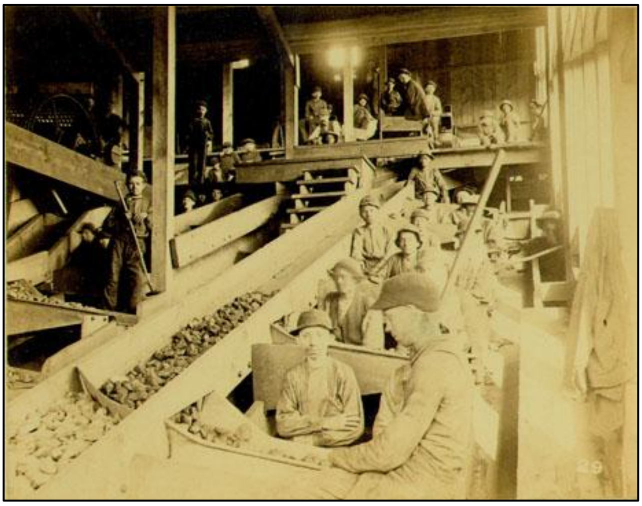

Fig. 3: Breaker boys[1] at North Ashland Colliery circa 1884 [7]

This process was limited in the particle size distribution that was practical executable. On the coarse side, the weight of the individual particles was the limiting factor whilst the overall throughput was the limiting factor on the fines side. According to Manouchehri [8], the process generally allowed for minimum particle sizes of 50–75mm with an upper particle size limit of 250–300mm. The following are some of the key operational factors that affected the efficiency of hand sorting:

- Working area - A suitable surface that is easy to install and maintain is crucial
- Type of material - The material to be picked should ideally be present in minimal quantities within the feed.
- Feed preparation - Washing or cleaning the feed is vital for improved material identification.
- Labor efficiency - Younger and quicker workers were often preferred for better productivity.
- Particle size - Optimal sorting occurs with material sizes averaging between 60 mm and 300 mm.

[1] A breaker boy was a coal-mining worker in the United States and United Kingdom whose job was to separate impurities from coal by hand in a coal breaker.

- Lighting conditions - Enhanced lighting significantly improves the performance of hand sorting.

With declining ore grades, decreased liberation sizes, shifts in economic scales, and recent technologies, hand sorting fell out of practice. This very labour-intensive method of beneficiating coal became increasingly impractical, uneconomical, and even unethical. By the late 1960s and early 1970s, the practice was mostly discontinued.

2.2 Jigging

Although the origins of jigging can date back centuries, jigging was first comprehensively documented in the 16th century in Georgius Agricola's *De Re Metallica*, which outlined the use of perforated baskets to manually separate ores in water. Early innovations have included introducing levers for carrying larger baskets. Piston and plunger pumps from the Industrial Revolution introduced hydraulic systems which led to mechanized jigs and ultimately, the basic principles of modern jigging systems.

According to Wills and Finch [9], the initial use of jigs in coal beneficiation can be traced back to the work of engineers like Baum who introduced water pulsation to separate the coal particles from the gangue material. The following schematic, shown in Figure 4, highlights the basic principles of a jig:

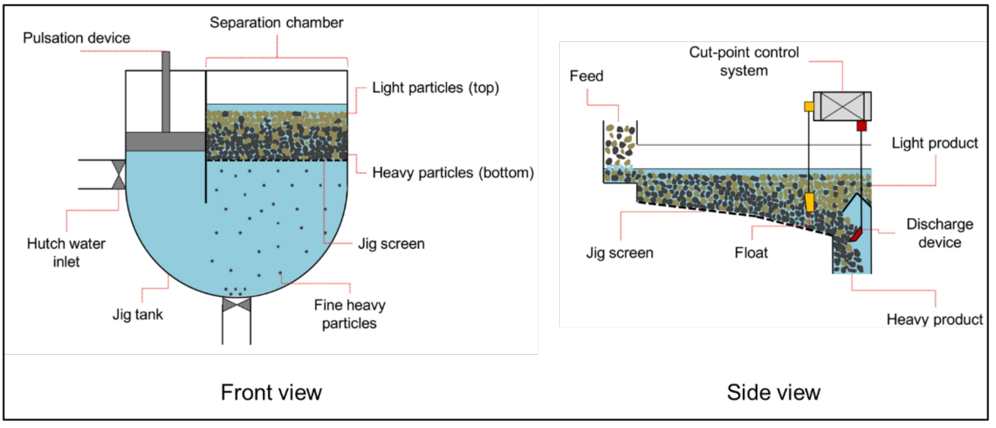

Fig. 4: General scheme of a jig [10].

Jigs are still a popular choice for coal beneficiation today mainly because of their relative simplicity and low operational costs. It seems however that they tend to be more efficient in treating the coarser particle sizes. It is worthwhile noting that liberation also plays a key role in this. In Figure 5, a simplistic comparison between the resulting effect of separation in a dense medium bath and a jig is shown.

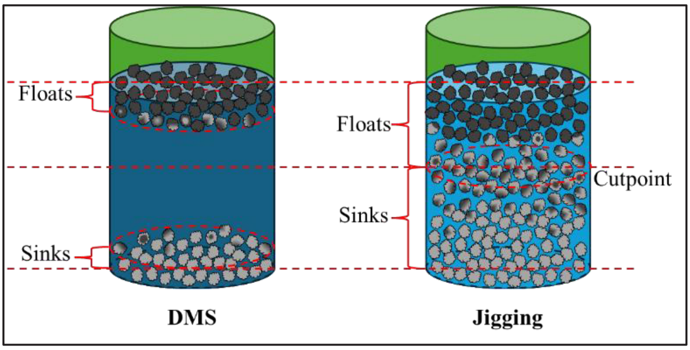

Fig. 5: Comparison between DMS and Jigging (Adapted from [11]).

The continued refinement and adaptation of jig technology ensures its enduring relevance in the coal industry, as it balances efficiency with environmental considerations.

2.3 Dense media separation

Commercially applied in the early 20th century, Dense Medium Separation (DMS) emerged as a transformative technology, particularly in the 1920s and 1930s, when the demand for higher-quality coal products grew alongside industrialization [5].

2.3.1.Historical development

The concept of dense medium separation has a historical origin that can be traced back to the observation made during the operation of early forms of jig washers. It was noticed that a concentration of fine grains of heavy minerals created a semi-stable suspension that acted like a heavy fluid, causing material of low relative density to float, regardless of size. This observation led to the deliberate inclusion of semi-suspended fines in water used for jig washer operation, as it was deemed a desirable component. The concept was further developed with the introduction of trough-and-cone washers, eventually leading to the emergence of the first commercial dense medium washing process known as the Chance process or "sand flotation process of coal washing" [11].

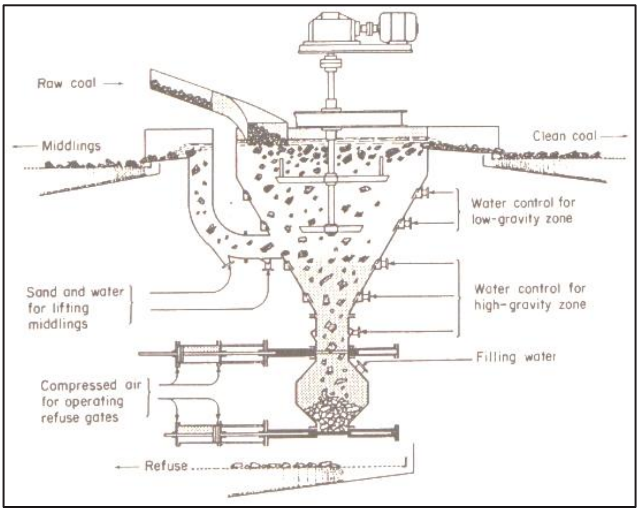

Fig. 6: Three-product Chance cone separator [11]

Chance's cone separator paved the way for the development of other processes utilizing different separating media, such as the Conklin process, using fine magnetite and water, the de Vooys process employing finely ground barite and loess, and the Wuensch process utilizing natural fine clay and slate. In addition to these processes, attempts were made to commercialize the use of saturated salts and organic liquids as dense media, such as the Lessing process based on a saturated solution of calcium chloride and the Du-Pont process employing chlorinated hydrocarbons. It was based on the separation phenomenon first reported by Sir Henry Bessemer in 1858. These processes were primarily utilized in anthracite coal cleaning due to their higher installation and operating costs [9].

The widespread adoption of dense medium baths or vessels in coal and mineral dressing applications gained momentum following the economic depression of the early 1930s. Significant developments in dense medium technology took place in the Netherlands, with the enhancement of the de Vooys process into the renowned Barvoys process and the introduction of new processes by Tromp using finely ground magnetite or pyrite. The breakthrough in dense medium separation came from the work of Staatsmijnen in Linburg, where the first dense medium separator was installed in a commercial plant in 1937, sparking global interest in dense medium methods [9].

2.3.2.Static separators

Dense medium baths can be divided into two main categories: deep baths and shallow baths. Both categories share essential similarities in their operation. Float products are effectively removed from the surface using paddles or the natural flow of the medium, with discard removal methods varying depending on the type of ore being processed.

Deep baths, such as the Barvoys, Tromp Deep Bath, and Chance Cone, provide a stable environment with extended residence times. This stability makes them less susceptible to fluctuations caused by excess water. The Barvoys, originally designed for barytes or shale, have successfully transitioned to processing magnetite. The Tromp Deep Bath also utilizes magnetite and employs elevators to remove discards and middlings. The Chance Cone stands out as a pioneering dense medium separator, utilizing coarse sand and incorporating elutriation principles [9].

In contrast, shallow baths require significantly less medium and occupy less space. They are further categorized into three types: wedge-shaped baths (like the Ridley-Scholes), circular pools (such as Drewboy), and horizontally mounted drums or discs (like Wemco). The industry trend was increasingly favouring shallow baths due to their space efficiency and lower medium requirements. This marks a shift from the earlier preference for deep baths, which were slower to respond to changes in medium density—a characteristic that historically benefited coal cleaning. The following are two of the most prominent technologies [12]:

The Drewboy separator, originally designed in France, is a washer system designed to clean raw coal with particle sizes ranging from 6 to 800mm, achieving processing capacities of up to 1000tph. The separator's vessel widths range from 0.5 to 5 meters, paired with wheel diameters spanning from 2.5 to 8 meters. A diagram (Figure 7) illustrates the unit's fundamental structure. While the inclined wheel configuration is predominantly used for coal cleaning, a vertical wheel variant is also available, specifically for processing smaller coal particles (6 to 120mm) at a reduced capacity of up to 100tph.

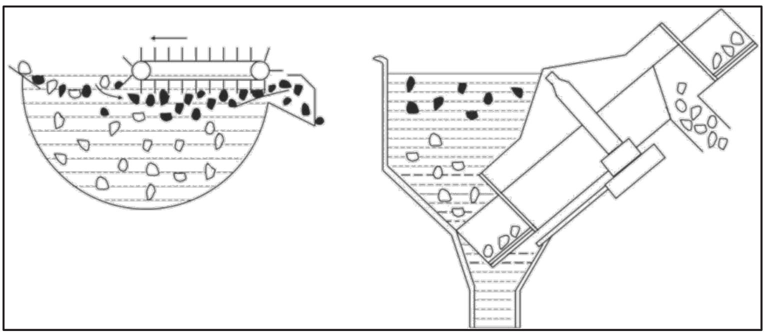

Fig. 7: Fundamental structure of a Drewboy separator [12]

The WEMCO drum separator has gained significant popularity as one of the most widely utilized dense medium baths. Known for its high efficiency, precise separation capabilities, and straightforward operation, it is also easy to maintain [9].

In this system, raw coal and the dense medium are introduced at one end of the drum. The clean coal, which floats, is carried over a weir at the discharge end and then transferred to a drain-and-rinse screen. Meanwhile, the heavier sink material is lifted from the bottom of the medium pool by lifters attached to the drum's interior. This material is then deposited into a central trough, where a flow of medium washes the waste onto a drain-and-rinse screen. For three-product separation, an additional compartment is incorporated, as depicted in figure 8. Skirt plates are used to create a central flow channel, preventing floating coal from being collected by the rotating lifters [9].

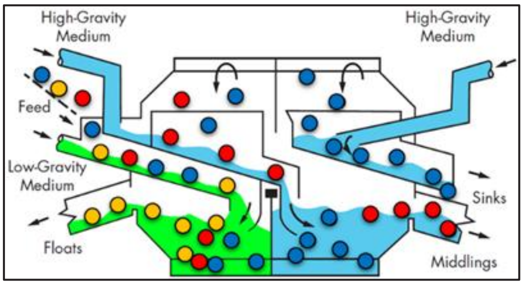

Fig. 8: Schematic of a three product WEMCO drum (adapted from [9]).

Two-product drum separators typically have diameters ranging from 2 to 4 meters and lengths between 3.35 and 6 meters, with capacities reaching up to 400 tons per hour (tph) for single overflow units. Three-product drums share the same diameter range but can extend up to 6.5 meters in length, with capacities of up to 325 tph [9].

2.3.3.Dynamic separators

By the mid-1950s, dense medium vessels became widely utilized for treating coarse coal that was too challenging for jig washers. However, a major limitation identified was the drop in cleaning efficiency with the decrease in the size of coal fed to the washer, typically below 5mm. The Dutch State Mines (DSM) identified the challenges in separating smaller-sized coal, primarily related to the viscosity of the medium used and the amount of medium removed with the washed products requiring regeneration. The solution to this issue was the development of the dense medium cyclone washer, pioneered by M.G. Driesen and colleagues at DSM in 1945 [11].

Napier-Munn [12] details the development and historical background of the dense medium cyclone (DMC). According to popular accounts [12], the DMC was first identified around 1942 by Dutch State Mines (DSM) in the Netherlands. The discovery occurred when a hydrocyclone used for processing loess - a type of clay medium - in a dense medium bath for coal cleaning became clogged. During the cleaning process, it was observed that the vortex finder contained a significant amount of clean coal, indicating that the coal was being concentrated in the cyclone's overflow. This observation led to further research and development of the concept. Despite the challenges posed by the German occupation of the Netherlands during World War II, extensive testing was conducted, culminating in the patenting of the DSM DMC in 1942. To commercialize and support the technology, DSM established a subsidiary called Stamicarbon, which licensed the technology to engineering firms and offered technical assistance. Stamicarbon created a design manual for its licensees, commonly referred to as the DSM bible. As can be seen from the following figure, although there were a few improvements over the years, a modern DSM cyclone still looks similar to the original design in the DSM bible:

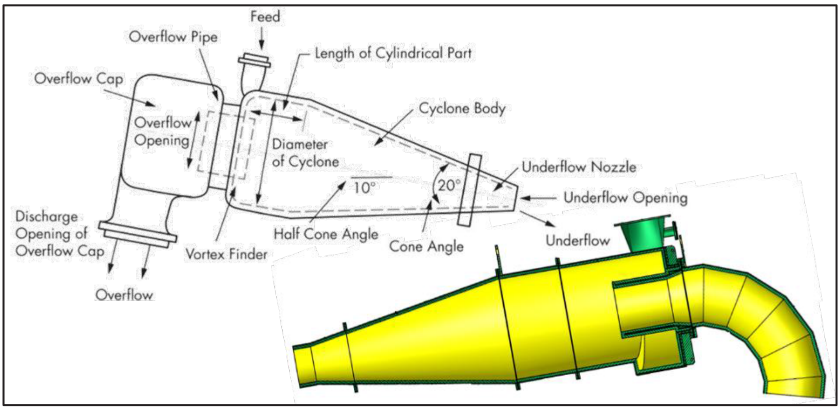

Fig. 9: The original DSM design (top left) vs. a modern cyclone (Adapted from [13] and [14]).

Over the following decade, the DSM cyclone technology emerged as a revolutionary advancement in coal washing, becoming the most significant development in the industry in the 20th century [11]. The DSM cyclone system was widely adopted, and numerous plants implemented cyclone types of washers, many of which were derived from the original DSM design. The following is a summary of the most prominent dynamic DMS equipment that evolved from the original design.

The Dynawhirlpool (DWP) separator was developed and patented by Victor Rakowsky in the United States in 1959 [15]. In essence, the unit is a cylindrical vessel with the length of the vessel typically about five times the inner diameter of the vessel. There are tangential and axial openings on both sides of the vessel which is normally installed at a 15^{o} to 25^{o} angle. The bottom tangential opening is where medium (magnetite and water) gets introduced into the unit and the top tangential opening is where the sinks particles exit the vessel. The feed gets introduced at the top axial entry point and the floats exit at the bottom of the vessel.

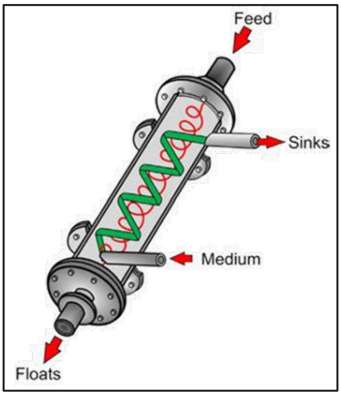

Fig. 10: The Dynawhirlpool separator [9].

It is reported that since the sinks material exits the vessel near the ore entry point, the vessel also experiences reduced wear rates, and since it is only the medium that gets pumped to the DWP, the operating costs are also lower. Furthermore, Hacioglu and Turner reports that the DWP has a high sinks capacity and is rather forgiving when it comes to variances in the expected product yield based on the feed washability [16].

The Tri-flow separator (TFS) is a direct derivative of the DWP and can be regarded as two DWPs joined in series. It was developed in the 1970s in Italy in an attempt to enhance the separation efficiency of a DWP [17]. The main advantage of the TFS is that it can be operated with two different densities of feed media which will then produce two different sink products of which the operator can control the specific density. In a coal handling and processing plant, the three distinct products that can be produced from a single TFS can therefore be high-quality coal, middlings coal, and discard.

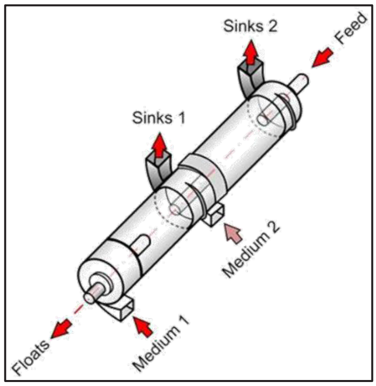

Fig. 11: The Tri-Flo separator [9].

In the 1980s the British Coal Technical Services and Research developed a unit that would be able to treat a wide size range of coal (up to 100mm) at high capacities in a single vessel. This unit was called the Large Coal Dense Medium Separator (or LARCODEMS in short). The unit consists of a cylindrical chamber with a tangential inlet for medium at the bottom. Similar to the DWP, floats exist axially from the bottom of the unit and the feed is introduced axially from the top. At the top of the unit is a tangential outlet connected to a vortex extractor. LARCODEMS are typically installed at an inclination of 30°. The very first installation of a LARCODEMS was at the Point of Ayr Colliery in Wales where the 1000mm unit treated 0.5 to 100mm particles at a feed rate of 250tph [9].

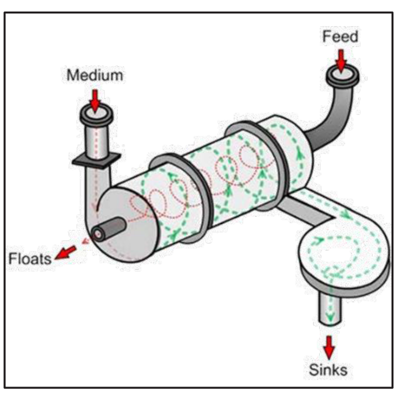

Fig. 12: The LARCODEMS [9].

The last dynamic DMS separator that will be highlighted in this paper is the three-product cyclone. Originally developed in Russia in the 1960s with further development in China in the 1980s [18, 19], the three-product cyclone consists of a primary cylindrical section (similar to a LARCODEMS), which then feeds a secondary conical section (very similar to a conventional DMS cyclone). From the literature [19], it seems like the motivation for the development of the three-product cyclone was to get to a simplified solution for two-stage coal washing as depicted in the following schematic.

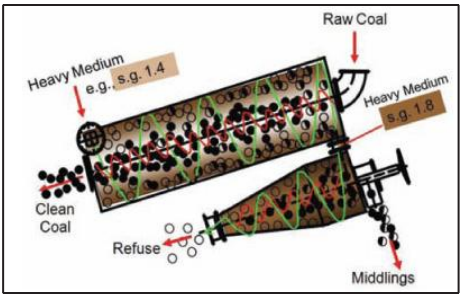

Fig. 13: Gravity-fed three-product cyclone [19]

With all the different DMS technologies in the market currently, it seems like the humble DMS cyclone is still the technology of choice in the vast majority of CHPPs. Tim Napier-Munn [12] mentions that: “it is difficult to see a serious competitor for the DMC in the foreseeable future in the processing of bulk commodities such as coal and iron ore.” Some of the main advantages of a DMS cyclone in a coal application, according to Napier-Munn include:

- Efficient separations at a specific density;
- Wide particle size that can be treated;
- High tonnage throughput for a relatively small footprint;
- Mature technology with relatively easy operation.

Furthermore, with the larger DMS cyclones currently available (up to 1.45m in diameter) to efficiently wash coarser coal particles, the need for DMS baths is also waning [9]. In fact, the majority of modern CHPPs are kitted out with DMS cyclones in a Coarse Low Gravity (CLG) and Smalls Low Gravity (SLG) circuit for a high-quality coal product. The sinks of these two circuits typically form the feed for a secondary wash in the High Gravity (HG) circuit that produces a lower-quality coal product. Figure 14 is a simplified flow diagram highlighting the typical flow of a conventional modern CHPP often seen in South Africa’s Witbank coalfields:

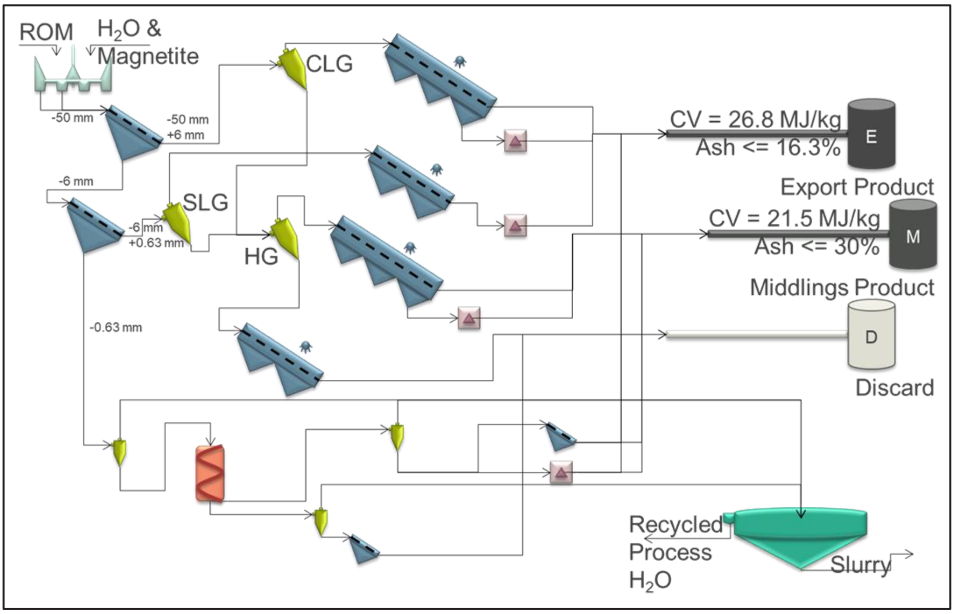

Fig. 14: Simplified flow diagram of a modern CHPP.

3 South African influence

Scholars reckon that the first recorded discovery of coal in South Africa was in the Western Cape in the late 17th century [20]. Coal mining in South Africa started in about 1864 when the first colliery opened near the town of Molteno in the Eastern Cape Province [21]. The earliest record of coal washing goes back to 1905 when the first five jig plants were installed in Natal Province [22]. In the early days of coal washing in South Africa the -10mm particles (termed "duff coal") were simply discarded because there just wasn't any market for coal of this size at that time.

Times have changed however, and there are now markets that can accept ultra-fine, thermal-grade coal. For South Africa, the change came in the early 1970s when South African coal companies landed a contract with the Japanese steel industry requiring low ash (7%) blend coking coal. DMS was found to be the only process able to deliver the required separation at relatively low separation densities and high amounts of near-density material in the ore [22].

Johan de Korte reported that some of the earliest work on the beneficiation of fine coal with a dense-medium cyclone was carried out in South Africa by the Fuel Research Institute (FRI) of South Africa under the guidance of Dr. PJ van der Walt in 1949 [23]. The biggest difference between a conventional coal DMS circuit and a fine coal DMS circuit is the fact that the fines DMS circuit makes use of wet drum magnetic separators directly after the DMS cyclones, instead of the conventional drain-and-rinse screens. Today, there are quite a few fines DMS CHPPs operational globally that reap the benefits of the superior efficiencies that can be achieved with DMS cyclones [23].

Besides the South African influence with the development of a specific DMS process, a proudly South African invention in the field of DMS was the Norwalt Washer. This was a bath-type washer where the feed was introduced in the middle of the vessel that was fitted with stirring arms. These stirring arms then whisked the floats off to the edge of the vessel whilst the sinks collected at the bottom of the vessel. Scrapers at the bottom of the vessel transported the sinks to an exit point at the bottom of the vessel into a sealed elevator which continuously removed the discard material [9]. The schematic in figure 15 gives an indication of the feed, product and discard streams of the Norwalt washer.

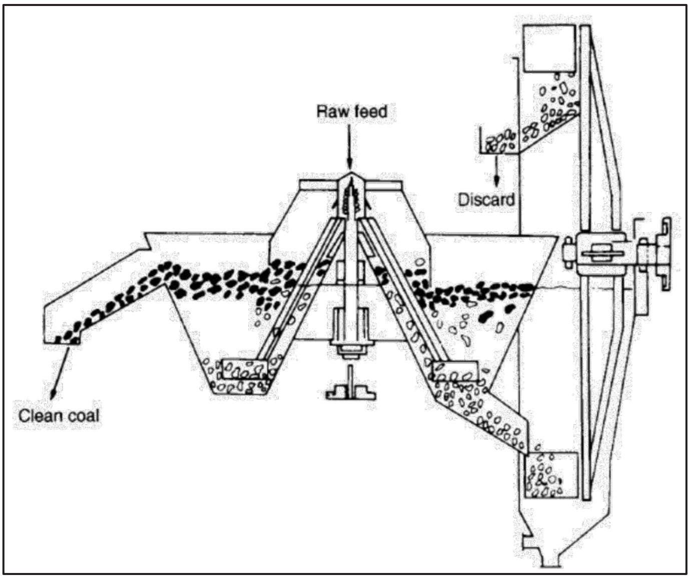

Fig. 15: The Norwalt washer [11].

It is a well-known fact that South African coal can be considered quite difficult to wash with relatively high values of near-density material and multi-seam mining processes. The markets South African coal is sold into are many and varied in required product specifications. All these conditions, together with South African expertise, contribute to the ideal incubator for innovative developments that will still see the light in the future.

4 Current and future trends

Innovations in the field of dense medium separation have always been motivated by the need for increased efficiencies, reduced expenses, or increased returns/yields. In recent years, we've seen a trend that the rise of environmental, social, and governance (ESG) consciousness also influences developments in DMS. Indications are that major developments in the near future might be in the following areas [24]:

- Advanced Process Control (APC): The use of APC systems along with machine learning algorithms.
- Sensors: Real-time measurement of process and equipment performance together with the use of Artificial Intelligence that will assist in process optimization and maintenance.
- Sustainable practices: Reduced energy consumption, minimizing water usage, and greener DMS technologies.
- Integrated technologies: Integrating DMS with other mineral processing techniques to achieve better recoveries and efficiencies.

- Tailings management: Mitigation of the environmental impact of waste disposal and retreatment of historic dumps.
- Digital twins: Develop digital twin models of DMS circuits to simulate and optimize operations before making changes in the actual plant.
- Circular economies: Opportunities for recycling and reusing materials within the mineral processing circuit to minimize waste and improve resource efficiency.
- Processing of low-grade ores: Investigate the processing of low-grade ores that were previously uneconomical to process.

The need for greater processing capacity and improved recovery rates drove significant advancements in DMS technology. The introduction of dynamic separators, such as cyclones, in the mid-20th century marked a major leap forward, enabling higher throughput and finer separation. Additionally, developing automated control systems and optimizing dense media recovery circuits reduced operational costs and minimized media losses. These innovations not only enhanced the economic viability of DMS but also expanded its applicability to a wider range of coal types and sizes. Today, DMS remains a cornerstone of coal beneficiation, with ongoing improvements in equipment design, media stability, and process control continuing to refine its efficiency and environmental sustainability.

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