The history and development of centrifugal separation in coal preparation 1939 - 2025

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Abstract. The development of Centrifugal Separation Technology for coal is discussed from its origins in the late 1930's to its global application in the present day. The discussion is based on the author's 50 years (each) industry knowledge, plus the experience and teaching from their mentors, including the technologists from Dutch State Mines (DSM) who invented and developed the technology from its conception in the 1930's.

Key Words: *Centrifugal Separation, Cyclone, Coal, DSM, Technology, Development*

1 1939 - 1949 Invention and initial application of the technology

In the 1930's Coal Preparation technology mainly consisted of Jig technology, sometimes with early Dense Medium Baths (DMB) of various designs, treating the larger sizes, to produce higher grade low ash products for domestic, industrial, rail and metallurgical markets.

The De Voys company from the Netherlands had developed a DMB, the Barvoys, which used ground Barytes (BaSO4), as the medium solids, which had a Specific Gravity (SG) of 4.4 t/m3.

In the late 1930's DeVoys was merged with the DSM, who themselves had developed a DMB using Loess (2.7 SG) as the medium solids.

Although less dense than Barytes, Loess could effect a stable medium at 1.4 SG. As the Barvoys was a deep vessel, medium segregation was an issue, however this was used to its advantage as a middlings product could be recovered from a tube mounted approximately half way down the vessel.

Attention was given to optimising the medium recovery circuit by using early versions of Hydrocyclones, developed by DSM, to classify and thicken the medium in place of using conventional sedimentation thickeners. The circuit was successful and allowed a simple, compact medium circulation and recovery system (Figure 1) [1]. Later in Europe ground natural shale discard (~2.4 SG) was used in place of Loess which was a highly economic alternative.

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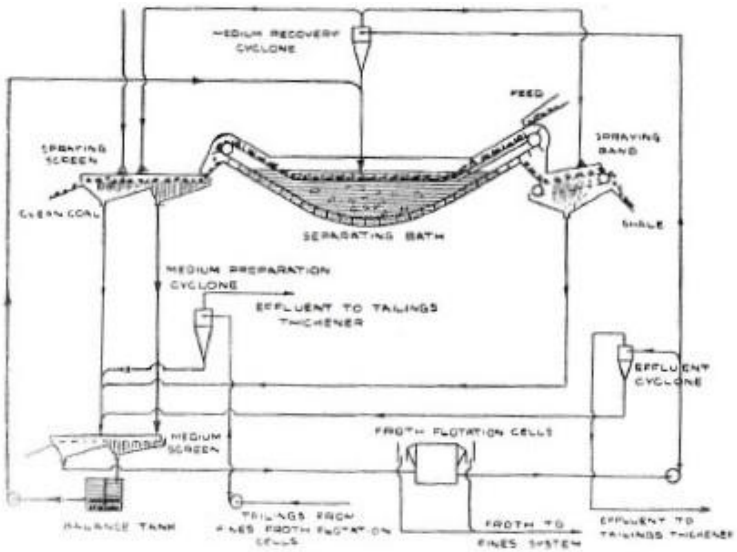

Fig. 1. Medium preparation circuit with classifying hydrocyclones

Several plants were built in Europe using this new classifying/thickening cyclone circuit. As with all plants, eventual wear on components resulted in holes in screen decks, which temporarily allowed oversize into the medium circuit. This would lead to blockages in the small diameter Hydrocyclones in the recovery circuit. In observations, initially at the Mauritz Mine in the Netherlands, it was noticed that the overflow of the cyclones was blocked with only clean Coal. The Hydrocyclones classifying and thickening the medium were, in effect, making a separation based on density.

During the war the concept of the Dense Medium Cyclone (DMC) was developed in the laboratories of DSM. This was done in secret because the Netherlands was occupied by the Nazis from 1940 to 1945. Without access to DMC technology for many years post-World War 2, the German Coal industry focused on improving Jig technology.

After a 15 tonnes per hour (t/h) Pilot Plant was built in 1945, the first commercial application of DMC's was installed in 1948 in the Netherlands.

The chosen medium for the DMC was magnetite, which was by then also being used as the medium solids in DMB's. This was because there was a ready supply of cheap magnetite in Europe and USA, and the Wet Drum Magnetic Separator offered a very high recovery of medium solids making the use of magnetite economically viable. High quality magnetite at 5.2 SG provided a stable operating environment with a much-reduced viscosity, compared to other medium types.

DSM designed the complete circuit for the Cyclone Plant in cooperation with its licensee appointed project engineering companies. This included the feed system, coupled with a two-stage magnetite recovery circuit which could maintain magnetite losses to less than 1 kg per t/h fed to the Separator as shown in Figure 2 [2].

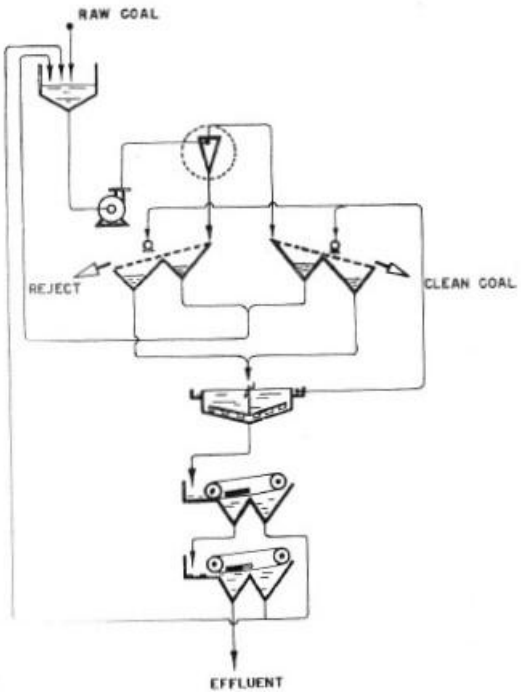

Fig. 2. Original DSM cyclone circuit

The first commercial plants used 500 mm (20") diameter (D) Cyclones. The geometry of the first DMC (Figure 3) was determined experimentally based on fixed parameters relative to the diameter of the unit. The basic ratios of the vortex finder diameter, under flow opening, and feed inlet were fixed as 0.4D, 0.3D, and 0.2D respectively. The feed pressure was a column height of 9D and the recommended volumetric feed solids of the Cyclone gave a coal-to-medium volumetric ratio of 1:3. The first DMC's were constructed from cast iron and later in Ni-Hard steel to improve wear characteristics.

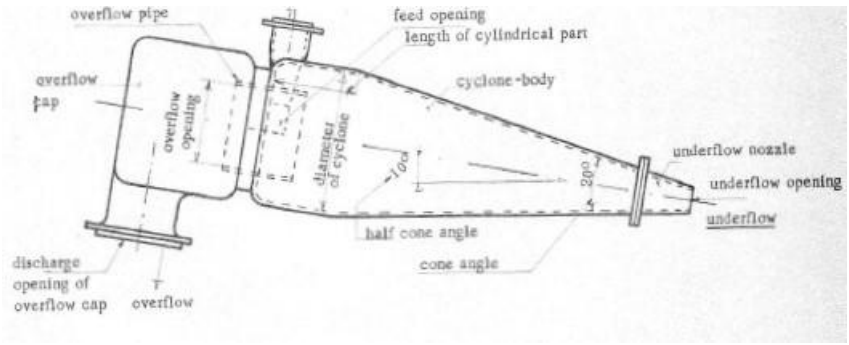

Fig. 3. Original DSM cyclone geometry diagram

As the DMC was developed from a classifying Hydrocyclone, the unit still classified the very fine medium solids so the underflow and overflow medium SGs were higher and lower than the feed medium. Consequently, the SG cut point in a DMC was seen to be higher than the feed medium SG and control of the medium solids size distribution was found to be

essential for maintaining a stable classification effect for efficient separation. Centrifugal forces were increased as the cone diameter decreased, enhancing the separation efficiency. This effect is incorporated by linking the specified inlet feed pressure to the cyclone diameter at 9D for Coal applications.

In later developed cylindrical Separators, the classification effect is less pronounced since the centrifugal force is constant, as the diameter of the unit is uniform thus reducing the classifying effect. Consequently, the general consensus of opinion is that the classic Cyclone design gives an improved result compared with a purely cylindrical unit of the same diameter.

2 1949 - 1960 Early commercial applications

In the 1950's the DMC technology was exported to other Coal producing countries such as Belgium, USA and the UK. In the USA, where Jig technology was prevalent on small coal, a great deal of research on the process was undertaken before the first full scale plant was built in 1958 at Jedda Highland Coal Company [3].

In South Africa the coal industry was only just developing. There were a couple of early Coal Preparation plants built as long ago as 1909 using a Baum Jig, and in the 1930's a Chance Dense Medium Cone plant was built [4]. The first Barvoys Bath plant on coarser Coal, was built at Hlobane Colliery in Natal in 1950. This plant was designed and supplied from the UK and was intended to use shale discard as medium solids, as used in the UK. The design company for the plant was Colliery Engineering from Sheffield, who were the global Barvoys and local DSM technology licensee. One of the author's mentors was the commissioning engineer for this plant. He recalled the six months he spent trying to operate the plant using a shale discard medium.

Of course, we know now the fundamental differences in the geology of Southern Hemisphere coals compared to European and North American Coals. Basically, in South Africa, the natural discard was unsuitable to create a stable medium as it has too low a density. To commission the plant, suitable rock had to be imported and then be crushed and ground to produce a suitable medium.

This is probably the first instance of Northern Hemisphere technology needing significant modification to process "Gondwanaland" Coals. This became a common theme with DMS technology also, which is discussed later.

In Australia there had been Jig plants built in the early 20th Century and Barvoys installations in the 1950's in New South Wales. The first DSM Cyclone plant was built in 1963 in Central Queensland by the first Australian DSM licensee.

In the mid 1950's, the South African government, wishing to develop its coal industry, decided to build a sophisticated semi-industrial scale pilot plant, with many different technologies and a flexible circuit to establish the best process route for the local coals.

The plant was built at the Fuel Research Institute (FRI) in Pretoria. It was again designed by Colliery Engineering UK, and initially included a Baum Jig, Barvoys Bath, Drewboy Bath, Froth Flotation Cells and the first DSM Cyclone in the Southern Hemisphere.

The engineer in charge of the FRI was one of the key figures in the development of Coal Preparation in South Africa: Peter Van der Walt. In operating the DMC in the FRI plant, Van der Walt, following the standard DSM operating parameters, struggled to get any efficient separation in the DMC and reported to DSM that the only solution he could find to make the Cyclone work at all, was to remove the underflow wear cone. This change in geometry significantly altered the DMC from the standard design cast in stone by DSM [5].

DSM were adamant that the problem was related to the quality and size distribution of South African Magnetite from the Palabora mine, not the Cyclone itself. A subsequent disagreement between Van der Walt and the engineers at DSM led sadly to an impasse, which continued until the end of his career.

In the late 1950's Van der Walt formed Nortons Tividale (NT) South Africa, a division of a UK coal preparation process company. His first development was the Norwalt DMB, which was specifically designed for South African coals and magnetite.

3 1959 - 1984 Alternative centrifugal separation technologies

In the 1960's the number of DSM plants constructed around the world, particularly in USA and the UK, increased significantly. Two plants were also built in Canada, at Smoky River and Sukunka and once more these were designed in the UK. Licenses were given to the leading coal preparation plant designers in many countries and the award of a DSM license was much coveted. By 1967 there were 31 DMC plants built in the USA by Roberts and Schaefer, the exclusive DSM licensee in the USA.

The technology was rigidly protected and policed by DSM. Scale up of the diameter of the original units from 500 mm, through 600 mm and 700 mm to a maximum of 750 mm for increased capacity, was slowly achieved. The DSM Cyclone geometry remained proportionally constant to that which had been developed for the initial 500 mm unit while the 1:3 coal to medium ratio was also retained as a standard.

In South Africa a licensee for the process was appointed but not NT, because of the ongoing 'feud' between Peter Van der Walt and DSM.

As an alternative to extend NT's portfolio, Van der Walt visited the USA and secured a license for the Dynawhirlpool Process (DWP) (Figure 4), the first centrifugal separation alternative to DSM.

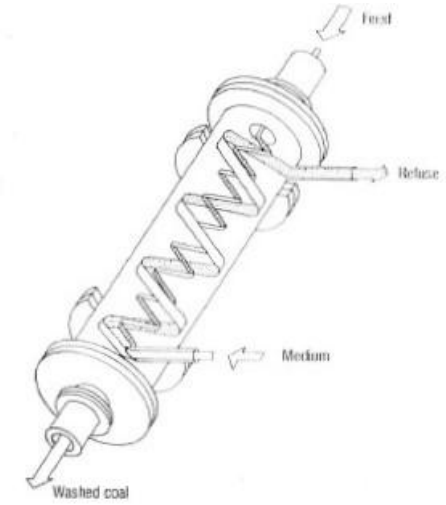

Fig. 4. The Dynawhirlpool

The DWP was developed by the American Zinc company to reject lighter quartzitic gangue prior to milling and recovery of very dense lead and zinc ores. The process was also adapted for use on small coal in the USA and several plants were constructed.

A significant reason for the development of the DWP was that to process denser minerals, the separation feed pressures of the feed medium needed to be much higher than for coal. This meant gravity feed in a DSM unit was impractical and pump feeding of a DMC at those pressures, with hard rock, was impossible with the pump technology of the time. The DWP had the significant advantage of the raw feed being admitted to the unit at atmospheric pressure into the air core.

NT adapted the DWP to South African coal processing. In subsequent years they built several plants in South Africa using the Norwalt Bath on the large coal fraction and the DWP on the small coal fraction.

Meanwhile, the initial local DSM licensee, having adapted the DSM technology to South African coals, built DSM Cyclone plants, usually coupled with WEMCO Drums treating the coarser fractions. Eventually the DMC / WEMCO Drum or Drewboy Bath circuit became the most popular design in South Africa.

The DWP's feed pressure advantage, compared with the DSM Cyclone, meant that the feed did not need to be elevated to 9 x the Cyclone diameter before mixing with the medium and falling by gravity into the DMC. At this time pump feeding DMCs were rarely employed.

Also, at this time other Centrifugal technologies were being developed. In Japan, an inverted DMC, called a "Swirl Cyclone", was introduced but did not gain any popularity outside Japan.

In the UK, the National Coal Board (NCB) developed the Vorsyl Separator (Figure 5). This development was primarily motivated by a reluctance to pay royalties to DSM for use of the DSM Cyclone process. The Vorsyl was used almost exclusively in the UK and was successful in processing coals with relatively easy washability characteristics. Plants built using the Vorsyl in other countries were less successful.

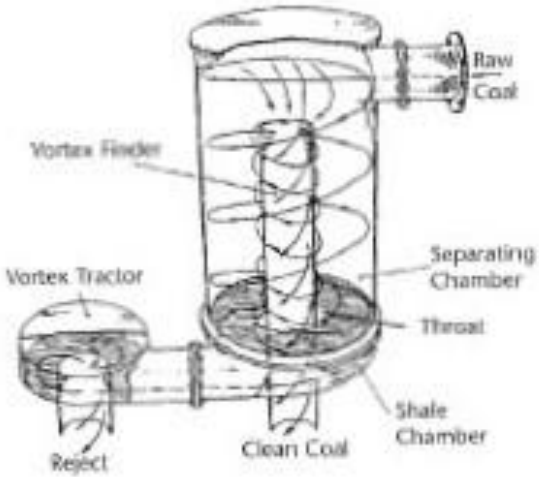

Fig. 5. The Vorsyl

In the early 1980's another significant development in DMC technology was made in South Africa with the construction of plants using Dense Medium technology on finer coal in the size range 0.5 mm to 0.1 mm. This was motivated by the relative difficulty in applying froth flotation to the fines in South Africa. Using DMCs on the finer coal fractions resulted in increases in overall yield of export grade coal.

DSM had experimented with treating finer coal using the DMC in the late 1950's. Two plants had been constructed in Belgium using this process, but the plants were eventually abandoned as the Belgian coal mines closed.

Fine coal Dense Medium plants were built in South Africa at Greenside and Newcastle Platberg collieries by NT, after successful pilot trials at the FRI in Pretoria. A similar plant was built at Rooiberg Tin on fine ore. In these plants the separation products could not be drained and rinsed on vibrating screens. This meant that multiple separate floats and sinks magnetic separation stages were required with interstage dilution to recover the products and remove contamination from the magnetic concentrate.

In India, the first DMC plant was built for Tata Iron and Steel (TISCO), in the 1970's at Jamadoba Colliery in the Jharia region. Jamadoba was the site of the first Coal Preparation plant in India built in 1952.

In 1981 the first large scale DSM cyclone plant in India was commissioned for TISCO at West Bokaro, in the Bihar region, to produce coking coal. The quality of the raw coal was extremely poor by all known standards, such that after crushing to minus 25 mm top size, to maximise liberation of coking values, a separation SG of 1.4 produced a product coking coal of only 18% ash. The near gravity material +/- 0.1 SG of the 1.4 SG cut point was over 90%. To this day, processing of Indian coking coal faces the same challenge.

The West Bokaro plant was designed in the UK using standard DSM parameters. Like the problems reported 20 years earlier in South Africa, the conventional Northern Hemisphere design criteria were found to be less applicable when processing coal with very high levels of near-gravity material.

The plant required adjustments to cyclone geometry and increases in the coal-to-medium ratio before a successful outcome could be achieved. The DSM cyclones were eventually replaced by modern units which allowed a much higher coal-to-medium ratio and consequent increase in the coal throughput. Two further UK designed DMC plants were built in the 1980's for Tata, incorporating the lessons learned from the first plant.

In 2021, amongst the other more modern plants built in India, a new 2 million tonnes per year state of the art CPP was built by Tata at Jamadoba, incorporating modern DMC's.

4 1984 - 2000 Demise of DSM, scale up and optimisation of DMC diameter and geometry

In the mid 1980's, with the initial DSM patents having expired, classifying Hydrocyclone manufacturers entered the DMC market. DSM struggled to control the technology globally and as the Dutch mines closed, DSM as a company abandoned the coal industry and reverted to chemical production. The influence of DSM in the coal industry declined. Eventually in the 1990's the licensing technology arm of DSM, Stamicarbon BV, which supported the technology was closed.

The new DMC suppliers had different strategies than DSM. Their initial DMC designs were basically larger diameter Classifying Cyclones, which had been developed for large grinding circuits in the metals industries.

The new DMC's had significant differences to the standard DSM design (Figure 6). Firstly, the shape of the feed entry was modified from a tangential shape to involuted. This change (which had been rejected by DSM), effectively smoothed the cyclone entry flow pattern and actually increased the cross section of the feed entry size, allowing a higher volumetric throughput. Secondly, the vortex finder diameter was significantly larger than the DSM standard which, coupled with the involuted feed opening, allowed higher coal-to-

medium volumetric ratios up to 1:5. This allowed flexibility and tailoring of the ratio depending on the difficulty of the separation.

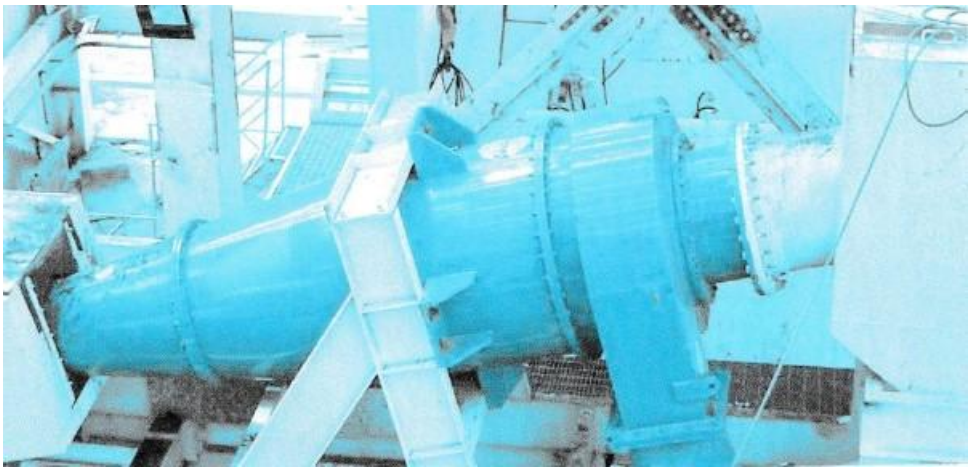

Fig. 6. Modern cyclone geometry

The cone angle and underflow orifice diameter on the new DMC's were similar to the DSM specification. Underflow solids capacity was not increased for DMCs of equal diameter to DSM units, but the new DMC designs included adjustable geometry to optimise performance as well as complete ceramic linings which significantly improved the Cyclone life.

Underflow solids volumetric capacity is still the normal limitation on DMC capacity, but the increase in diameter of the modern units and hence the underflow volumetric capacity, allows much higher throughputs.

The modern DMC suppliers increased the DMC diameter beyond 750 mm diameter, which was the largest DSM unit. In an unsuccessful effort to keep control of the technology, DSM produced evidence that diameters larger than 750 mm would affect separation efficiency as the centrifuge forces would be significantly reduced [6]. However, this did not stop larger diameter DMCs being installed firstly in Australia and shortly followed by South Africa [7], thereby increasing capacity and the particle size which could be treated.

Pump feeding of the DMC's became the common method as the quality of slurry pumps improved. This eliminated the need to elevate the DMC feed to 9 x the diameter above the unit. In addition, the adoption of a mixing box or "Wing Tank" twin pump feed system in place of the original single pump centre tube system, allowed the plant height to be reduced and accurate measurement of circuit SG in the rising pipeline from the circulating medium pump (Figure 7).

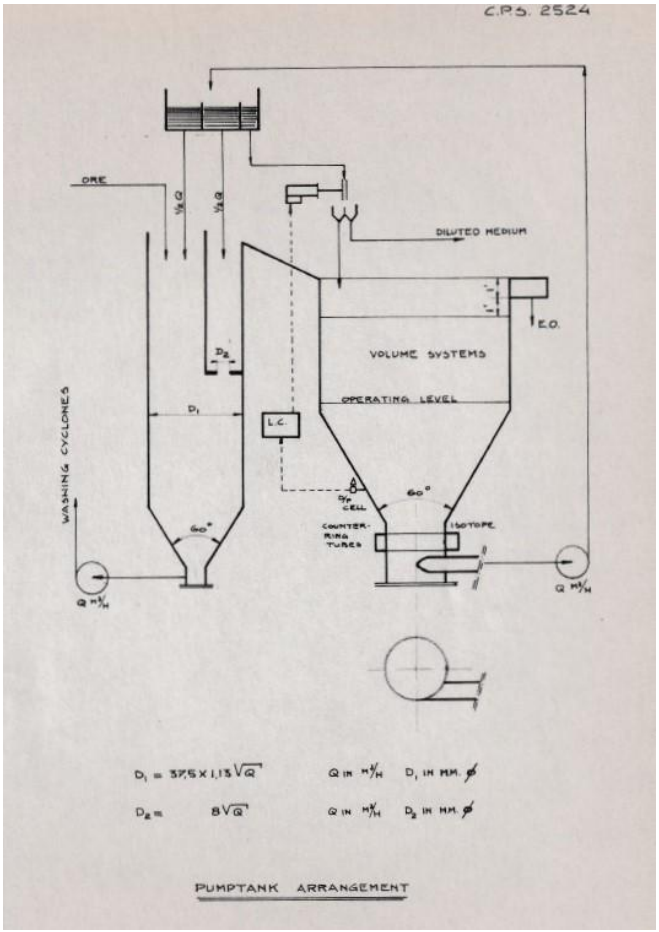

Fig. 7 Pump feed system

Another development in the 1980's, which assisted the introduction of the larger diameter DMC's, was the development of water-based gravity separation technologies such as spirals and upward current separators, to process the 1 mm x 0.1 mm material. This meant that the desliming operation ahead of the DMC, traditionally made at 0.5 mm, was raised to 1 mm or even 2 mm. This proved a successful development in removing the most difficult particle size to treat in the newly enlarged DMC's and significantly improved the screening operations and medium recovery of the DMC plant.

In the early 1980's in the UK, most plants for steam coal employed Baum Jigs due to the relative ease of separation, with minimal near-gravity material. However, the performance of the Jigs was erratic due to lack of raw coal homogenising facilities in compact urban mine sites.

The National Coal Board (NCB) instigated a research program to develop a Centrifugal Dense Medium Separator which could accept up to 100 mm feed size at a feed rate of 250 t/h and improve performance and capital cost compared to a Baum Jig. The outcome was the (Large Coal Dense Medium Separator) or LARCODEMS (Figure 8).

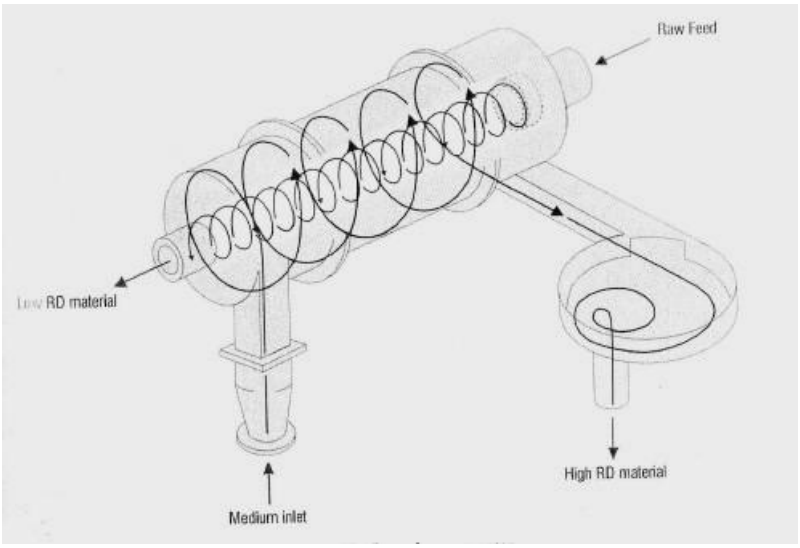

Fig. 8 LARCODEMS

The LARCODEMS was a cylindrical vessel of 1.2 m diameter, similar in concept to the DWP, with the feed introduced to the eye of the Vortex at atmospheric pressure, thus allowing larger feed particles to be processed. The sinks outlet was fitted with a "Vortextractor" controlling the back pressure on the sinks outlet. The vortextractor was developed by NCB from its original design on the Vorsyl Separator.

A 50% sized pilot unit was installed in a UK plant in 1983, and the first commercial plant was commissioned at Point of Ayr Colliery in North Wales UK in 1984. Several other LARCODEMS plants were built in the UK during the next few years, until the UK nationalised coal industry declined and was privatised in the 1990's.

The initial design of the LARCODEMS had one drawback and this was a tendency of larger flat discard material to skip down the air core and be discharged along with the clean coal. This feature was largely irrelevant when power station coal was the product, but as the miners received domestic large coal as part of their salary, even the odd piece of stone in this supply was unacceptable. To resolve this issue the LARCODEMS length was increase by approximately 1 m, which largely alleviated the problem.

After the decline of the NCB (or British Coal as it was latterly called), the LARCODEMS technology was sold to a licensee and was exported to several countries. It was also used on Iron Ore with some success.

Around the same time as the LARCODEMS was introduced, the Tri-Flo dense medium separator was developed in the University of Trieste in Italy. The Tri-Flo was basically a double DWP with a second chamber, where primary floats were re-treated, with either the same medium SG to give a "double pass" to improve efficiency, or a lower SG medium to produce a clean coal and middlings from the second chamber.

The Tri-Flo was installed in a 800 t/h plant in Sardinia at Carbo Sulchis. In addition, a second smaller installation at Tabas in Iran was built in the 1990's.

5 2001 - 2010 Large single stream concept

In the new millennium, DMC design continued to be upscaled and it was the basis of almost all the large new plants in Australia and South Africa [8]. As there was no longer any

premium market for +50 mm coal, the raw coal was reduced in size prior to the separation process.

In the USA and Russia, DMB's continued to be used in tandem with DMCs, as the ability to vary cut points in the large and small coal sections was perceived as an advantage in optimising clean coal yield [9].

The advantages perceived in installing very large DMC's up to 1 500 mm, coupled with a parallel increase in the associated unit equipment in the circuit, allowed single unit DMC streams of 500 t/h to be installed. To achieve this, vibrating screen widths of up to 4.2 m width were developed, along with larger dewatering centrifuges and slurry pumps.

The installation of large single unit processing streams was pioneered in Australia. One of the perceived advantages of large single unit designs was the elimination of DMC distributors, which were required for multiple smaller DMCs to achieve the same feed capacity. The available designs of DMC distributors were poor in providing homogenised feed to each smaller DMC unit. Consequently, the overall efficiency of a bank of smaller DMC's was poorer than with a single unit. The new large diameter DMCs, although employing lower centrifugal forces, were seen to match or improve performance, compared to a multi-unit DMC system when treating feed with a bottom size of 1-2 mm.

In addition, modern advances in technology on Wet Drum Magnetic Separators eliminated the need for secondary magnetic separator circuits. As a result, magnetite losses from DMC circuits are now generally significantly less than the early guaranteed figures of 1 kg per t/h of DMC feed.

6 2010 - 2024 Further scale up and the emergence of Chinese technology

The DMC continues to be the dominant centrifugal separation technology for coal in the major coal producing countries. DMCs are available in diameters up to 1 500 mm, capable of processing a feed of almost 1 000 t/h in a size range up to 100 mm.

In the last 15 years the emergence of Chinese technology has spread globally from its home base and is now being seen in several Western countries. The Chinese systems feature a 3-Product Cyclone (Figure 9), a hybrid device using a large diameter cylindrical vessel as a primary separation chamber, with the primary sinks being directed to a conventionally shaped, smaller diameter, secondary DMC, where the Middlings and Discard are separated.

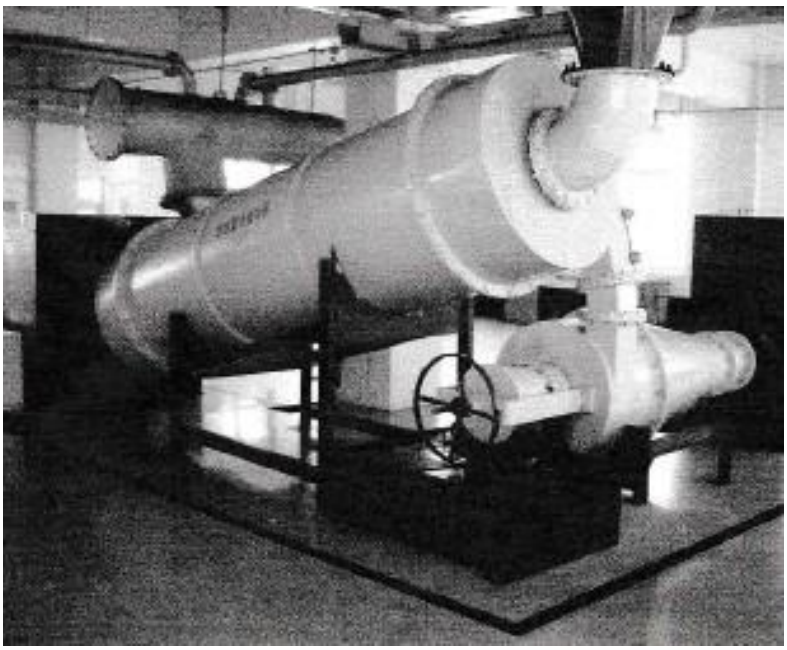

Fig. 9. Chinese 3-Product cyclone

In addition, the system can be configured without a desliming stage ahead of the primary vessel. This option is a unique feature, which offers an advantage in upgrading fine coal in the same vessel as coarse coal and then recovering the fine products from the medium recovery circuit.

There are variations in the circuit, where the fines processed in the vessel are re-processed in separate fine coal DMC's.

Advancement in Wet Drum Magnetic Separator technology, with much more powerful magnets, has made the recovery of magnetite using this design viable, whilst circuits employing a desliming system at 1 mm aperture, and separate fines processing, will still lose less magnetite. Figures of losses are quoted in the order of 1-2 kg per t/h feed to the Chinese system, including fines treatment.

The Waterburg region of South Africa has seen the development of an interesting new and unique flowsheet. This system employs the LARCODEMS as a primary 'De-Stoning' stage at a high SG of separation, for 100 mm top size raw coal, with the primary clean coal being crushed to minus 50 mm and then reprocessed in two stages of conventional DMC's. This significantly reduces the discard load on the DMC's.

This system, which is employed in South Africa's largest coal preparation plant complex, utilises the LARCODEMS in its original application for which it was developed in the UK. The subsequent two- stage DMC system ensures a highly efficient plant performance.

Finally, there is renewed interest globally in separate fine coal DMC systems, facilitated by the improvements in magnetic recovery seen with the modern Wet Drum Separators.

In recent years a great deal of development work has been done on Spirals and Upward Current Separators to achieve lower SG cut points on the (1 × 0.15) mm raw coal fraction. The objective of this being to increase overall clean coal yield by lowering the ash content of the fine coal product, so that there is reduced loss of yield from the DMCs to compensate for a higher ash fine coal product in the target product ash.

Of all potential technologies used for processing coal of (1 × 0.1) mm size, the fine coal DMC, although the most expensive option available, presents the best alternative to effect the lowest SG of separation and highest efficiency on finer coal, to minimise any compromise in the separation SG of larger sizes to achieve the maximum yield of low ash, high value products.

7 Future development

There will hopefully be continual improvement in Centrifugal Dense Medium Separation. The authors believe it will still be the dominant technology used for the processing of coal in the next decades. The centrifugal separation process is now over 80 years old but still represents the last 'quantum leap' in coal processing technology.

Time will tell if new separation technologies eventually replace the current systems.

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This paper is dedicated to our mentors at Head Wrightson Colliery Engineering in the UK, DSM in the Netherlands and Norton's Tividale in the Republic of South Africa:

Charles Corbidge, Head Wrightson - Chief Coal Preparation Engineer
Gordon Wade, Head Wrightson - Deputy Chief Coal Preparation Engineer
Herbie Driessen, DSM Stamicarbon BV - Director
Josef Mengelers, DSM Stamicarbon BV - Chief Technologist
Albert Basten, DSM Stamicarbon BV - Senior Technologist
Peter van der Walt, Nortons Tividale Republic of South Africa