DMS cyclone modelling at De Beers

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Synopsis

This paper discusses the current approaches to modelling the DMS cyclone within the De Beers group. Current efforts are split into short-term value-adding process understanding and longer-term semi-fundamental analysis of separation mechanisms.

To date, the basic applied approach has yielded significant value to the group, enabling operators to focus on simple diagnostic measures to control their process. The more involved modelling approach has given rise to a new understanding of the separation field, in particular that the high density gradients within a cyclone are highly localized, indicating that separation of medium to heavy density material takes place low in the cone. The model has proven to be conceptually robust, but still requires further development and validation to become a complete modelling and simulation tool for De Beers.

Introduction

Despite cyclone technology being well established throughout various process industries, performance modelling of this technology still enjoys considerable attention, a fact that is testament to the poorly understood nature of its operation. De Beers is heavily dependent upon DMS technology, as this forms the primary bulk reduction step in the diamond winning process. A typical industrial DMS system can process in the order of 800 tph, while only selectively recovering less than 1%. Current means of assessing how effectively these systems operate is by:

- ➤ medium tracer tests, which characterize the integrity of the FeSi
- ➤ densimetric analyses, which measure densimetric split of ore to floats and sinks
- ➤ and bulk sampling of DMS tailings, which is a reprocessing of material with DMS technology to check for misplaced diamonds.

Recent densimetric testing[1] has indicated that throughout the De Beers operations, there is a wide range of DMS performance, some of which can potentially result in significant revenue losses to tailings. Therefore, DMS modelling is a critical activity that must satisfy the following goals:

- ➤ be technically detailed enough to assist in understanding separation mechanisms
- ➤ but also consist of content that can be practically applied such that value can be realized in the short-term.

This paper outlines the detail behind the semi-fundamental modelling approach currently being developed for De Beers operations as well as the practical data-driven modelling that is being employed to address immediate inefficiency issues. It is envisaged that the semi-fundamental approach will not only assist in fully understanding separation mechanisms, but also help to assess the long-term future of dense medium separation technology in the group.

The current state of DMS systems

For all its virtue, the specification process of DMS systems is largely reliant on in-house experience, whether this refers to internal De Beers specialists or suppliers and manufac-turers of cyclone equipment. The fact that there are numerous DMS and DMS system configurations shows that the general approach to implementation is not well developed, even though there may be differing process conditions across the group.

Feed rate to be treated is the main criteria, with general throughputs assigned to specific sized cyclones. The ancillary specifications, including head, etc., are quite varied in their implementation.

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Apart from nameplate specifications, historically, the monitoring of performance has heavily relied upon tracer tests, conducted without gravel. Not fully realized at the time was that a pressurized system with three phase flow reacts completely differently from just medium only. In effect, the tracer test acted as a test for medium integrity, but was too often taken as a measure for overall cyclone performance.

In addition to this is the impact of operators, which are governed primarily by production call. More often than not, DMS cyclones would be taken past their specified capacity and to the end point of their physical operation. Experience has shown that at this point, control comes down to physical inspection of the underflow (by camera) where it is determined if there is yield or not. This is quite extreme, but if nothing else, serves to process sufficient tons under pressure.

Practical modelling to improve efficiency

There are many examples in the De Beers group of densimetric profiling of sinks and floats from DMS products. Prior to 2000, the interpretation of this type of data was limited as there was no correlation to revenue losses, or perhaps even the belief that cyclones could fundamentally be inefficient.

Basic conceptual process estimations by Petersen[2,3] attempted to address the quality of the feed to the DMS as having a major influence on process efficiency. The underlying principle is that the often large quantities of fine material, -4 mm, in DMS feed would effectively change the viscosity of the medium. The effect is similar to that of blanketing or entrainment of larger particles, which then gives rise to upward shifts of the cut point. The important feature of the phenomenon is that it is a modification to DMS operation, which detracts from the DMS's ability to separate particles based on density alone. While this is not the only problematic situation being faced throughout De Beers operations, it does highlight that the DMS is quite a 'sensitive' process.

The practical roll-out of this theory included calculation of an 'efficient feed rate' based on:

- Amount of material above 2.7 rd, calculated as a per cent of volumetric flow rate through the spigot
- Average interparticle distance as fed into the cyclone, calculated from the particle size distribution and volumetric flow rate for the cyclone
- Measured pressure fluctuations for a range of feed rates during operation
- Pressure and density interlocks associated with overall circuit stability.

The rationale behind this is to ensure that:

- there is enough space for particles to separate in the cyclone, understanding that the separation field is relatively weak and most of the material separates relatively low in the cone section
- a high percentage of fine material, say -4 mm material, at a given feed rate, significantly reduces the average particle distance of the feed. In effect, this material acts like separating medium and the resulting impacts can dislodge larger particles from achieving their 'natural' separation zone
- a cyclone with a low feed pressure variability will be more efficient. High variability comes with having both too much throughput and too little throughput. Therefore, understanding and identifying the 'sweet spot' is also a good diagnostic tool for assessing the impact of ore on DMS stability
- without a stable overall DMS system, changing feedrates achieves little. Therefore, standards are extremely important to maintain.

The above approach has yielded significant value throughout our operations. Prior to this type of work, there was a limited expectation that DMS efficiency could be improved at all. Not only has there been improved efficiency, but reduced feed rates have also brought improved utilization, which gives the added advantage of improved $/hour.

Semi-fundamental modelling

The above discussion actually trivializes the steps taken to understand the separation mechanisms in the cyclone such that operational improvements can be made. There has been significant effort put into conceptualization and delineating the most important mechanisms.

This section gives specific detail to some of the ideas that are being used to construct a semi-fundamental model for the purpose of providing a conceptually correct DMS specification and operational tool.

Figure 1 shows a schematic outlining the process of finding (a) the flowrate and (b) the structure of the FeSi concentration as well as other useful operating characteristics, i.e. flow split. The exact details of each step are now given.

Flowrate equations

The first part will deal with the set of calculations that form the FeSi topology. The point of departure is initially to assume a given flow rate, Q. The radial velocity, $U(r)$, for a cyclone geometry is calculated as

$$U(r) = \frac{-Q}{2\pi r\left(B + \dfrac{(D/2 - r)}{\tan(\theta_c)}\right)} \qquad [1]$$

where $U(r)$: radial velocity, Q: total flowrate, r: radial position, B: Barrel length, D: Cyclone diameter and θ_c: cone angle.

From here, the next steps involve determining the size of the aircore such that the proposed inlet flowrate, Q, is satisfied by the combined flow rates at the overflow and spigot. Note that this radial velocity equation is an approximation of the exact solution, considering the axial velocity components that reduce the radial component toward the air core. The equivalent approximate tangential velocity component, $V(r)$, is

$$V(r) \sim \frac{V(r_o)r_o}{r} \qquad [2]$$

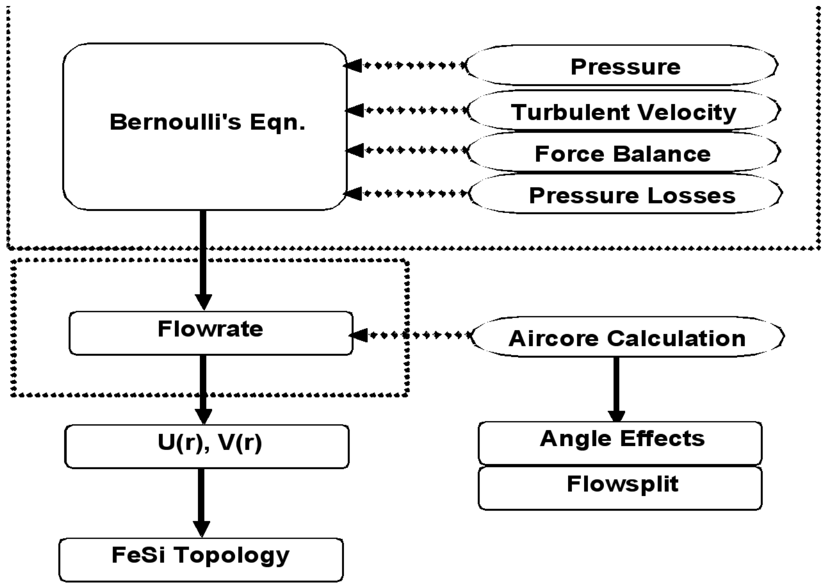

Figure 1—Schematic of calculation scheme for determining DMS flow parameters

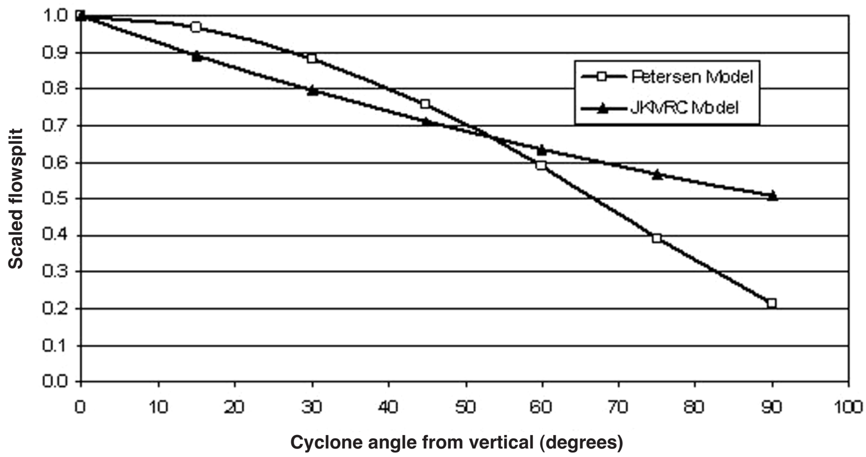

Figure 2—Scaled flow split as calculated by model and compared to that of Asomah and Napier-Munn (1997)

where $V(r_o)$ is the tangential velocity at the cyclone wall, r_o. Now with good approximations for the radial and tangential velocities, the rotating fluid potential can be calculated at the point where the fluid rises beyond the outlet radii for both the overflow and spigot. The conditions at both outlets are slightly different, where the overflow has an air core potential out of the outlet and a negative component of gravity. The spigot has a similar air core potential, a positive component of gravity potential and a slight negative component from the cone angle. Apart from the potential flow, the spigot region also has momentum from the cone region as the medium is funnelled toward the spigot. The resulting axial velocities are:

$$W(overflow) = \sqrt{2\left(V_a^2 - ag\cos(\theta_i)\right)\left(\frac{b}{a} - 1\right)} \qquad [3]$$

$$W(spigot) =$$

$$\sqrt{2\left(\begin{array}{l} V_a^2\left(1 - \cos(90 - \theta_c)\right) + \\ ag\cos(\theta_i) \end{array}\right)\left(\frac{b}{a} - 1\right)} + \frac{|U_a|}{\tan(\theta_c)} \qquad [4]$$

where W is the axial velocity, V_a is the tangential velocity at the aircore, a is the radius of the aircore at a particular outlet, b is the outlet radius of a particular outlet, θ_i is the angle of inclination of the cyclone, θ_c is the cone angle and U_a is the radial velocity at the aircore.

In order to apply these equations, the aircore is adjusted until the outflowing flow rate is equivalent to the flowrate used in Equation [1]. Once complete, the internal radial and tangential velocities are also determined, albeit they are simplifications of more detailed solutions.

Figure 2 shows model results in the form of the flow split (a scaled version). It is compared to the JKMRC model[4], which has also been scaled in order to compare the fundamental forms of each model. The JKMRC model is based on a series of cyclone tests and, subsequently, an exponential fitting term was used to fit the data. The model proposed here clearly shows the same decrease in flow split as the cyclone is tipped on its side. However, the form is inverted as compared to that of the model by Asomah and Napier-Munn (1997). Without experimental validation, the point is not to disprove the form of the other model, but rather to highlight that the flow split change for a range of cyclone angles is similar to that of the JKMRC model, which is based on experimentation. The benefit of the proposed model is that it is based on semi-fundamental equations, which should allow for a better extrapolation of the model for a wider range of conditions.

FeSi differential

This section continues the model development by translating the calculated radial and tangential velocities into a structure that allows a better understanding of how FeSi is 'organized' within the cyclone. FeSi has long been modelled as a diffusion process[5], but it is subjected to the same hydrodynamic forces as any other two-phase flow, except for the fact that the volumetric concentration is high enough such that it creates its own pressure profile.

The proposed model considers the FeSi/water medium to be similar to the flow of liquid through a porous medium, which follows Darcy's law, viz:

$$U_d = \frac{1}{R}\frac{dP}{dr} \qquad [5]$$

where U_d is the average velocity of flow through the media, R is a resistance term dependent upon porosity, FeSi size, etc and dP/dr is the pressure drop over a particular element. The method used to apply this equation is as follows:

- Assume that fully developed porous flow is equivalent to the movement of FeSi through water or, alternatively, water through FeSi
- Divide cyclone radius up into a number of equally spaced elements, say 10
- Compare the calculated FeSi movement velocity, U_d, to the radial velocity in order to determine acceleration of FeSi against radial flow
- Allow neighbouring elements to interact via a coupled differential equation approach
- Calculate final FeSi movement in allocated residence time
- Recalculate new FeSi density after movement of media, assuming that the resulting velocity is equivalent to a change in FeSi contained volumes.

Figure 3 shows an example of the density results for a 510 mm cyclone. Clearly, from the wall of the cyclone at 0.25 metres, there is initially a slight increase in density from the 2.65 rd (feed) to approximately 2.72 rd. By 5 cm from the wall, the density drops back to 2.65 rd, but thereafter for the next 10 cm stays fairly constant until 12 cm from the centre of the cyclone. From this point, the density rises sharply to almost 3.4 rd, then falls off just as quickly at the air core.

This profile shows that the density topology is relatively weak, except around the air core. Therefore, it would be assumed from this result that the regions of separating density, viz. > 3.0 rd, are very localized in the cyclone, possibly along the core and in the spigot.

The other comparison made is between a cyclone with a barrel extension and one without. The result with a barrel extension shows that the strength of the density topology is simply weakened, given that all else is still the same, i.e. flow rate, etc.

The reason for the shape of this profile is based primarily on the differential nature of the tangential velocity, where the FeSi media is moving toward the air core under radial forces, but is pushed back toward the cyclone wall as the tangential velocity increases. This effectively creates a zone of impact for the FeSi, i.e. general inward movement against outward settling under centrifugal forces.

The small increase in density close to the wall is due to the radial velocity close to the wall being relatively high, but then drops off in the main body of the cyclone due to the increasing length of the cyclone body in the cone, viz. from wall to air core, sectional volume initially increases, but then decreases closer to the air core. Therefore, the model clearly states that the density profiles developed are sensitive to cyclone geometry.

The only validation of this part of the model comes via the work of Lyman *et al.* (2002), where gamma ray tomography was performed on a magnetite cyclone at the JKMRC. Figure 4 shows an example of a particular cross-section of the cyclone operating at 1.2 rd. The structure clearly shows a slightly higher density near the wall, lower in the main body, and then higher close to the air core. At the aircore, the density falls below that of the feed. Structurally,

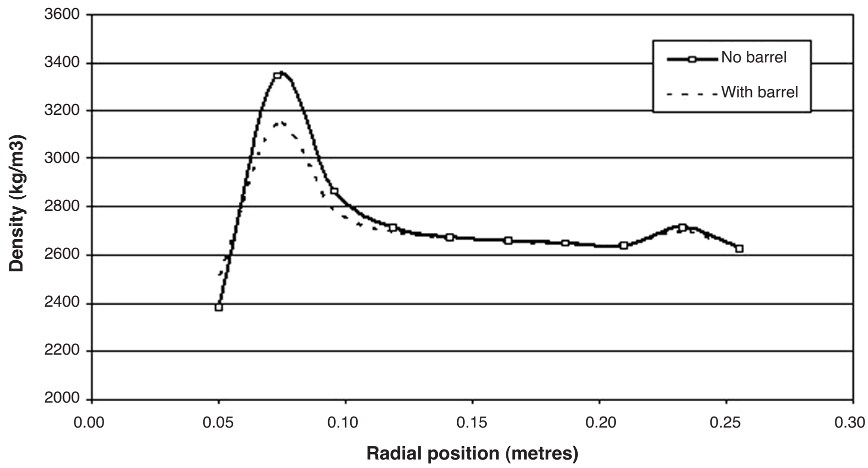

Figure 3—Radial density profile from air core to cyclone radius using a density element determination method

it appears that the model is behaving correctly. The next step for this work is to turn the model into a two-dimensional representation. The work of Lyman *et al.* (2002) shows that the increased density at the air core is localised lower in the cone around the spigot. From the spigot upward, the strength of this topology decreases, which is most likely weakened by viscous dissipation of the velocity.

Flow rate calculation

The estimation and calculation of the actual flow rate for use in this model is the key to developing a robust representation of the entire process. To date, this has been the most difficult part of constructing the model, and is still in progress. More than a mathematical problem, the solution requires more measurements to be taken during the operation of industrial cyclones, i.e. additional pressure measurements prior to the inlet.

The relationship between pressure and flow rate is not well understood by most practitioners, particularly since an operating system contains a non-Newtonian fluid. The major issue is as follows:

- Under most conditions, the inlet pressure measurement measures the static component of the head
- If energy is not in the static head, then it is either in the movement of fluid, viz. the flow rate, or it is dissipated in viscous losses
- Determining the split in energy between the flow rate and viscous losses requires a better understanding of how three-phase fluids dissipate energy
- The point above could be solved by installing more pressure measurement devices along the length of the feed pipe, or having a better mathematical knowledge of multi-phase non-Newtonian fluid flow.

Apart from this, the estimation process is reasonably simple (refer to Figure 5). Bernoulli's equation is applied as per standard practice in any fluid flow problem. The difference with this procedure is that the viscous losses are incorporated. A turbulent velocity profile in the feed pipe is assumed. Both the kinetic energy and loss term in Bernoulli's equation are functions of velocity, which can be estimated from the turbulent velocity equation. The velocity is found by using a separate force balance to determine when the system is at equilibrium, which then leads to an estimate of the velocity.

The major weakness is the equation for viscous losses, which is solely derived from Newtonian physics, and underestimates the overall system loss.

To date, there is no data-set against which to validate the model. Moreover, it is not possible to show conceptual results as the model relies on pressure measurements. This task is left for a follow-up investigation.

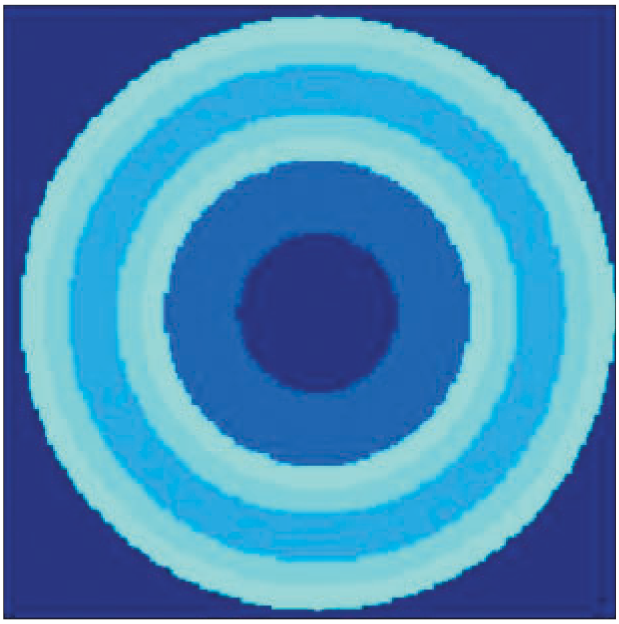

Figure 4—Cross-section density bands in a cyclone treating magnetite at 1.2 rd. Higher density clearly evident close to wall and inside aircore

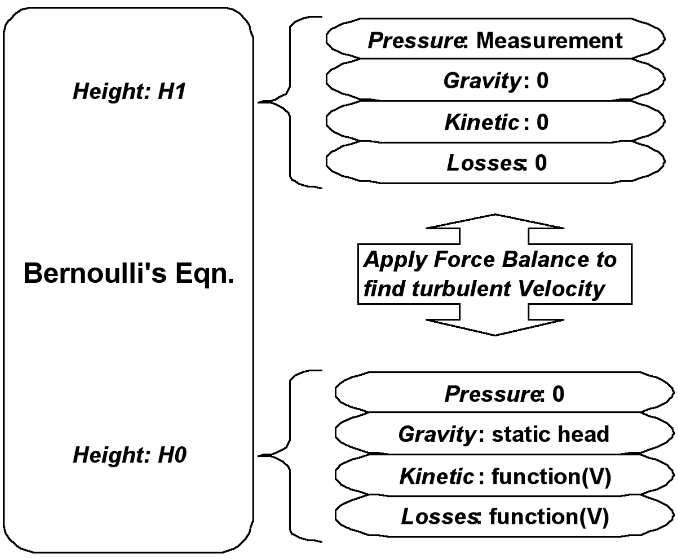

Figure 5—Procedure to back calculate the DMS feed velocity (flow rate) by using Bernoulli's equation in conjunction with a force balance on the multiphase fluid

Cut-point prediction

The model development is not at a stage where cut-point prediction has been developed. The major challenge is that this model provides a density topology or density map with which to calculate particle separation. Historically, many models have reduced the cut-point calculation to a few terms at most, which obviously trivializes the complexity of the actual separation process. Nevertheless, even with more tractable process information from this new model, it may be more difficult to finalize the model such that it gives stable and sufficiently accurate cut-point estimations.

Summary and conclusions

The current modelling focus at De Beers is a two-pronged approach, viz:

- simple, practical process equations that help to identify efficiency improvements in the short-term
- more complex modelling that specifically identifies the characteristics of separation and the underlying mechanisms.

To date, the first applied approach has been extremely successful, realizing significant value for the De Beers group. It has not only affected efficiency, but also helped to stabilize DMS systems that are now better utilized, providing increased $/hour. The success of this approach has been based on keeping the concepts simple.

The longer-term semi-fundamental modelling has progressed well and, to date, has provided significant insight into how DMS cyclones set up their separation field. What is surprising is that the model shows that the high density FeSi gradients are highly localized in the spigot and cone region. This fact, validated by JKMRC tomography work, implies that the effective separation volume is relatively small compared to the actual size of the cyclone. Of course, this interpretation very much depends on the *in situ* density distribution being fed to the cyclone.

With heavier and denser material being encountered lower in De Beers mining pits, this feature of the DMS cyclone becomes a potential problem, with ore now separating lower in the cyclone body. The process design implication is that more cyclones will be required to treat the same tonnages, given that efficiency remains the single most important prize.

Looking forward, it is easy to forsee that in a diamond processing context, the DMS cyclone as it currently is, may not be the single solution to life of mine bulk reduction requirements. At the very least, mines are encouraged to reassess their equipment needs and operating strategies on a relatively short–term basis, i.e. every two years.

From a supplier's point of view, they would be best served by strategically rethinking their own in-house knowledge on DMS operation and more aggressively marketing their range of products to solve efficiency problems, rather than just to treat required tonnages.

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JKMRC and MEI join forces to produce 7th edition of classic mineral processing text

Butterworth-Heinemann, a division of Elsevier, has announced the publication of a revised edition of *Wills' Mineral Processing Technology*, by Barry Wills and Tim Napier-Munn.

Wills' Mineral Processing Technology provides practising engineers and students of mineral processing, metallurgy and mining with a review of all of the common ore-processing techniques utilized in modern processing installations.

Now in its seventh edition, this renowned book is a standard reference for the mineral processing industry. Chapters deal with each of the major processing techniques, and coverage includes the latest technical developments in the processing of increasingly complex refractory ores, new equipment and process routes.

This new edition has been prepared in collaboration with the prestigious JK Minerals Research Centre of Australia, which contributes its world-class expertise and ensures that this will continue to be the book of choice for professionals and students in this field.

Barry Wills is senior partner with Minerals Engineering International, UK, and Tim Napier-Munn is professor and former director of the Julius Kruttschnitt Mineral Research Centre, University of Queensland, Australia.

Full details of the book can be found at www.min-eng.com/general/bookstore/1.html. ◆