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The dense medium cyclone – past, present and future

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ABSTRACT

Since the dense medium cyclone (DMC) was first patented in the 1940s it has become the process of choice in coal preparation, and is also widely used for upgrading iron ore and in the pre-concentration of diamonds and metalliferous and industrial minerals. It is in every sense a mature technology. This paper summarises the history of the process, considers its current status in mineral and coal processing, and suggests ways in which the process might evolve. Aspects reviewed include the process principles, process models, the importance of medium behaviour, particle size limitations, process analysis, instrumentation and control, and increases in scale. Particular attention is given to the potential for the use of larger cyclones at lower heads in mineral separations, as practiced in the coal industry. Using operating examples and published modelling results, the paper makes the case that these conditions will work in minerals too, and should be adopted. This will significantly improve the economics of DMC mineral separations at a time when pre-concentration is becoming more important for upgrading lower grade ores.

1. Introduction

The dense medium separation process (DMS) is a mature technology, and is widely used in mineral and coal processing. The dense medium cyclone (DMC) is the most ubiquitous of the DMS vessels in use, and deservedly so. It is efficient (when run properly), can process both coarse and fine sizes, and has a relatively small footprint. Unlike other forms of gravity concentration, it also makes a positive separation at a desired density cut-point, due to the presence of the medium whose density is easily controlled.

This paper briefly reviews the status of the DMC process, highlights some particular aspects of interest, and suggests some improvements to current design practice in (high density) mineral applications. The paper is not intended as a comprehensive review of the DMC or its literature, ancient or modern.

2. A Brief history

The invention of the DMC and its subsequent history is related in Napier-Munn et al. (2013). The accepted mythology is that the DMC was 'discovered' in about 1939 by Dutch State Mines (DSM) in Holland when a hydrocyclone processing loess (a clay medium) for a dense medium bath in coal cleaning blocked. While being cleaned out it was noticed that the vortex finder was full of clean coal, suggesting that it was being concentrated in the cyclone overflow. Investigation and development of the principle followed, and after considerable testwork during the German occupation of Holland in the Second World War the DSM DMC was patented in 1942, together with ancillary equipment such as the sieve bend. DSM formed a company, Stamicarbon, to licence the technology to engineering companies and to provide technical support. Stamicarbon produced a design manual for its licencees which over the decades probably became the most widely photocopied confidential document in mineral processing history. Decades after the expiry of the Stamicarbon patents, the Australian Coal Preparation Society has recently produced a modern version of the manual with additional updated material added (Mathewson and Ryan, 2013).

The first applications of the DMC were in coal, reflecting its origins, and the first large-scale use in minerals was probably at Williamson's Diamonds in Tanzania in 1955 (Chaston and Napier-Munn, 1974). Since its invention, there has been relatively little change in DMC technology other than increases in scale, advances in wear materials (eg polyurethane, and ceramic tiles) and some changes in the geometry, particularly of the inlet (Bosman, 2003; Honaker et al., 2010). There have also been various pretenders to the cyclonic separator throne including the Dyna Whirlpool, Tri-Flo, Vorsyl and Larcodems separators (Wills and Napier-Munn, 2006), all of which have found some application in industry, but the original DSM cyclone principle (Mathewson and Ryan, 2013) is still the most commonly employed.

DMCs are widely used in coal preparation, and are also used as the primary concentration step in the recovery of diamonds, in iron ore concentration, in pre-concentration of base metals, and in some industrial minerals. The operating medium density will depend on the

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application. In coal it is generally less than 1.65 RD and in minerals it is generally more than 2.5 RD. Accordingly coal applications use magnetite medium (a natural material) with a density of about 4.5–5.2 RD, and mineral applications use the more expensive ferrosilicon (FeSi, a manufactured product) with a density of about 6.7 RD. These differences are significant in understanding the performance of DMCs, especially in terms of the rheology and behaviour of the medium which is process-determining (Section 3.1).

3. DMCs - What We Know Now

3.1. The principle of separation in DMCs – Medium behaviour is process-determining

The scientific literature on hydrocyclones for classification, dewatering and thickening is very large. This is not true of the DMC, probably because of the difficulty of characterising density separations (Section 3.4) and the complexity of the system, involving as it does a dense medium suspension whose segregation in the cyclone is itself process-determining. There has been an increase in recent years in the application of computational fluid dynamics (CFD) to understanding the principles of separation in DMCs (Section 3.2), and these studies are making good progress. However the understanding is still incomplete.

Dimensional analysis gives the following relationship for the cut-density of the DMC, δ_{50} (Napier-Munn, 1984):

$$\left(\frac{\delta_{50}-\rho_f}{\rho_f}\right) = k\,Re_i^{-\alpha}d^{-\beta} \tag{1}$$

where ρ_f is the feed medium density, Re_i is the inlet Reynolds Number, d is particle size, and k is a constant. This conforms in general terms to a re-arrangement of the well-known equilibrium orbit hypothesis of hydrocyclone classification to the DMC (Napier-Munn, 1984):

$$\delta_{50} = \rho_f + K\left[\frac{D^3\eta}{Qd^2}\right] \tag{2}$$

where D is the cyclone diameter, η is the medium viscosity, Q is the flowrate, d is particle size, and K is a constant. Eqs. (1) and (2) imply that the cut-density in a DMC is always greater than the medium density and this is indeed what is observed in normal practice (there can be exceptions in cases of unusual medium conditions). They also capture correctly, at least in sign, the effect of cyclone diameter, flowrate and particle size.

However Eqs. (1) and (2) suggest that the cut-density increases with medium viscosity, whereas the consensus of the literature is that in real systems the reverse is true; cut-density *decreases* with increase in viscosity. This is because these models implicitly assume a stable medium (like a liquid) which does not itself segregate in the cyclone. In practice of course this is not the case; real media are composed of dense solids suspended in water, which partition in the cyclone, leading to a density differential between the underflow and overflow media products, the underflow usually being of higher density than the overflow. It turns out that ore partitioning in the DMC depends to a significant extent on how the medium itself segregates. This leads to some very simple but useful empirical expressions for the cut-density, δ_{50}, in terms of this medium behaviour, such as:

$$\delta_{50} = a_0 + a_1\rho_f + a_2\rho_u \tag{3}$$

where ρ_f is the feed medium density, ρ_u is the underflow medium density, and a_0, a_1, a_2 are coefficients determined from data and specific to a given system. This correlation was found to work both with magnetite media (Davis and Napier-Munn, 1987) and with FeSi media (Napier-Munn, 1984), using density tracers to determine the cut-density.

A common (though not very complete) measure of DMC inefficiency is the Ep, defined as:

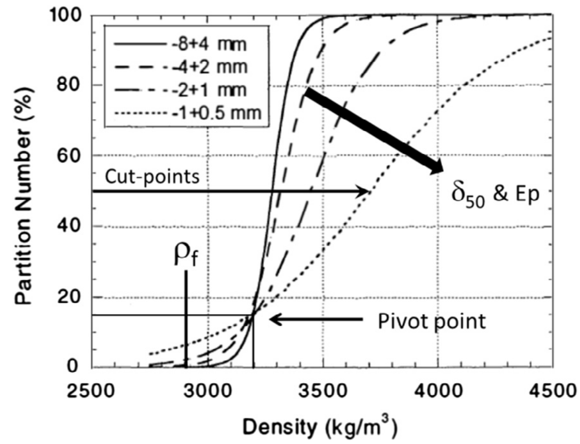

Fig. 1. Model prediction of partition curves for 400 mm DMC in iron ore concentration (from Dunglison, 1999).

$$Ep = \frac{\delta_{75}-\delta_{25}}{2} \tag{4}$$

where δ_{75} and δ_{25} are the densities corresponding to mass recoveries of 75% and 25% respectively. So Ep effectively measures the width of the central section of the partition curve (Wills and Napier-Munn, 2006), a wider curve indicating more misplaced material and therefore a lower efficiency. Ep is generally correlated positively with cut-point, so a relationship of the form of Eq. (3) will work for Ep as well (though of course with different coefficients). Fig. 1 shows this correlation, as well as the increasing cut-point with decrease in particle size, the fact that cut-point indeed exceeds the feed medium density, and the 'pivot point' phenomenon which is apparent in many such separations and was in one case used to model the DMC (Scott and Napier-Munn, 1992). In theory the partition number for the pivot point should be equal to the medium split to the underflow, and this has been shown to be true for stable media which do not segregate in the cyclone (Napier-Munn, 1980). However for unstable media (ie the media used in practice) this equality depends on the medium solids concentration and the underflow-overflow density differential (Scott and Napier-Munn, 1992).

Feed density ρ_f in Eq. (3) is an operating variable which is known for a particular system, but ρ_u has been found to be a function of operating conditions, including medium viscosity. Certainly all the published evidence is that the properties and behaviour of the medium, including its viscosity (Napier-Munn, 1990), are process-determining. Any useful model of the DMC must therefore incorporate the behaviour of the medium. The two most comprehensive process models in the published literature, those of Wood and Dunglison (Section 3.2), both incorporate medium properties and behaviour into their process predictions.

Medium behaviour depends in turn on medium properties, including solids density, size distribution and shape. For example, Fig.2 shows how the selection of FeSi medium grade (shape and size distribution) leads to different process outcomes in the processing of a particular iron ore in a 610 mm DMC, based on predictions of the Dunglison model.

The five FeSi grades to the left are milled (irregular shape) with fineness (and thus cost) increasing from left to right. As fineness increases (higher viscosity) Fe recovery increases, yield increases, and product Fe grade decreases, at the same cut-density (3.6 RD in this case). The two grades to the right are atomised (rounded shape, lower viscosity), C60 being finer than Special Fine. Atomised media, being of lower viscosity than milled, are generally used where the cut-density and thus medium density needs to be high. They show similar trends with fineness as the milled media but quite different overall behaviour, product grade being much higher than that achievable with the milled media, and recovery and yield being lower. Fig. 2 demonstrates the importance of selecting the correct medium grade for the application.