TECHNICAL NOTES 6

MANUFACTURED-MEDIA GRAVITY SEPARATORS

GRAVITY SEPARATION

Differences in the density of individual particles can be exploited to effect a separation and concentrate the desired components. The driving force for separation can be the gravitational field of the earth or the vastly more intense fields that can be generated by centrifugal action.

Gravity separation operations can be classified into two broad groups: manufactured medium and autogenous medium devices. In the former class, the separation takes a place in a liquid medium that is manufactured to have a density intermediate between the densities of the materials that are to be separated. Examples are the dense-medium drum and the dense-medium cyclone. In autogenous medium devices, the particulate material itself makes an environment that has an effective density that will induce separation of particles of different densities by stratification. Examples of autogenous separators are the jig, the sluice, the Reichert cone and the water-only cyclone. A third group of gravity separators that rely on more complex physical processes to effect a separation between particle of different density include the spiral concentrator and the shaking table.

6.1 Manufactured-Medium Gravity Separation

The most common manufactured media used in industry are slurries of finely ground magnetite or ferrosilicon in water. The effective density of such a slurry can be controlled by adjusting the concentration of suspension. The size of the particles that make up the suspension must be much smaller than the particles that are to be separated. In order to be useful as a separating medium, the slurry must be stable over the required range of densities which means that the suspension should not settle appreciably under gravity or in a centrifugal field if that is to be used to achieve separation. The suspension should also have low viscosity to promote rapid relative motion of particles that are to be separated. The medium must be easily separated from the two products after processing and for economic reasons the medium must be readily recoverable for re-use. Typical solids, with their respective specific gravities, that have been used for manufactured media are silica (2.7), barite (4.5), magnetite (5.18), ferrosilicon (6.8) and galena (7.8). The medium should be cheap, readily available and chemically stable. Suspensions of finely ground magnetite and ferro silicon satisfy these criteria. Magnetite is generally cheaper than ferrosilicon and the latter is generally used only for separation and recovery of high density minerals such as diamonds. Dense media manufactured from magnetite are commonly used for the cleaning of coal and for the recovery and concentration of a wide variety of minerals such as iron ore, manganese ores, cassiterite, fluorite and others. Magnetite media typically have densities in the range 1250-2200 kg/m^3 and ferrosilicon suspension in the range 2900-3400 kg/m^3. Mixtures of magnetite and FeSi can be used for the manufacture of media of intermediate density.

The principle of dense medium separation is quite straightforward. The material to be separated is placed in the dense medium in which the lighter particles float and the heavier particles sink. The floats and sinks are then separated. Equipment to effect the separation vary widely in mechanical design since it is quite difficult to achieve efficient separation continuously. Centrifugal separators are considerably simpler in design than gravity separators.

6.2 Quantitative Models for Dense-Media Separators

Four identifiable physical factors define the separating performance of manufactured media separators: the separating density or cutpoint, the separating efficiency, the short circuit of feed to underflow and the short circuit of feed to overflow. These effects are best described by means of a partition curve.

Three typical partition curves for a dense-medium cyclone are shown in Figure 4.1. These curves show how material of different specific gravity will partition to the float fraction. Other dense-medium separators have similar partition curves. These partition curves reveal the four operating characteristics.

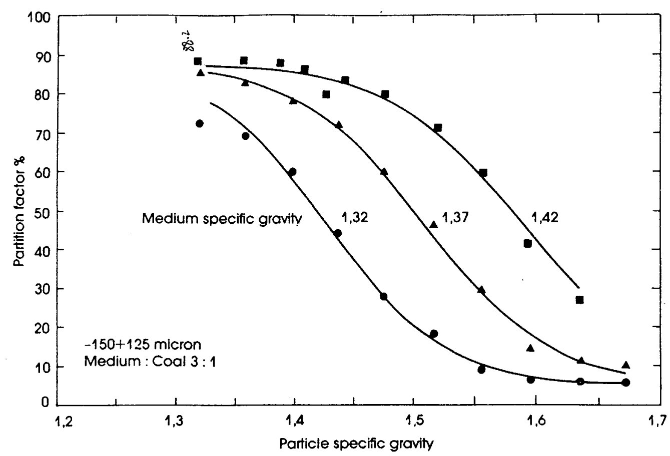

Figure 4-1 *Measured partition curves for different particles sizes in a 150 mm dense-medium cyclone.*

6.2.1 The Cutpoint

The cutpoint is defined as the density ρ_{50} at which the partition function has the value 0.5. A particle having the density ρ_{50} has equal chance of reporting to the sink fraction as to the float fraction.

The cutpoint is an operating parameter that can be controlled fairly easily by variation of the medium density which obviously determines which particles tend to sink in the medium and which tend to float. In a static bath of dense medium the cutpoint is always equal to the density of the medium. However, in continuously operating equipment this is not always the case and the cutpoint can be greater or less than the medium density depending on whether the lighter or heavier fraction must move counter to the prevailing bulk flow of the medium in the equipment. For example in the dense-medium cyclone, the medium together with the material to be separated enters tangentially on the periphery of the cylindrical section and the bulk of the medium leaves through the vortex finder on the axis. There is therefore an overall flow of medium from outside inward and the inward velocity of the medium tends to drag particles with it towards the center. Any heavy particles that leave the cyclone in the underflow must move against this flow and therefore require a net negative buoyancy to overcome the viscous drag of the medium. Thus any particle that finds an equilibrium orbit in the cyclone must be denser than the medium. Since the particles on equilibrium orbits define the cut point

$$\rho_{50} > \rho_m \tag{6-1}$$

where ρ_m is the density of the medium. The difference ρ_{50} - ρ_m is called the cut point shift and this can be normalized with respect to the medium density to form the normalized cut point shift

$$\text{NCPS} = \frac{\rho_{50} - \rho_m}{\rho_m} \tag{6-2}$$

The normalized cut point shift must obviously increase as particle size decreases and experimental data for coal in a dense-medium cyclone are correlated by the simple power law

$$\text{NCPS} = 0.4\, d_p^{-0.32} \tag{6-3}$$

over the range $0.015 < d_p < 1$ mm.

When the lighter fraction must move counter to a prevailing flow of medium, the NCPS must be negative. This is quite uncommon because dense medium drum separators are usually designed to provide an medium flow counter to the prevailing force field to ensure that the medium does not settle under gravity or the centrifugal field. This means that the sink material moves against a prevailing flow of medium and the cut point shift is positive. In general the NCPS can be neglected for dense-medium drum type separators for particles larger than a few millimeters.

An additional factor that influences the cut point shift is the settling of the dense-medium suspension particularly in centrifugal separators. This inevitably leads to a density differential between overflow and underflow media. The cut point shift increases with increased media density differential.

The partition curves usually normalize well with respect to the cut point density so that partition curves determined at different medium densities will be superimposed when they are plotted using a normalized abscissa ρ/ρ_{50}. This effect is seen in Figure 4.2 where the experimental data of Figure 4.1 are plotted against the reduced or normalized density ρ/ρ_{50} and the data fall on a single curve..

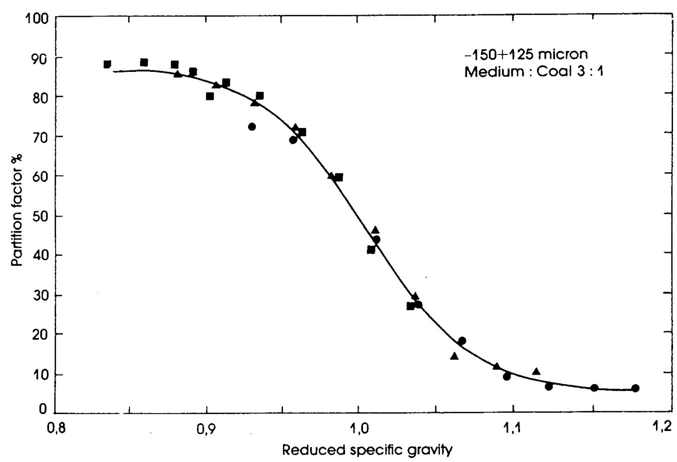

Figure 4-2 *Normalization of the partition function for a dense-medium cyclone. The presence of short circuit flows is clearly evident in this data.*

6.2.2 Short circuit flows

The curve shown in Figure 4.2 is called the normalized partition curve and it is represented by the symbol $R(x)$ where x represents the normalized density ρ/ρ_{50}. The general characteristics of normalized partition functions are shown in Figure 4.3 and in practice the low- and high- density asymptotes are not at 100% and 0% respectively. A fraction of the feed is assumed to pass directly to the underflow and another fraction to the overflow directly without passing through the separation field of the separator. If α is the short circuit fraction to sinks and β the short circuit flow to floats, the actual partition factor R can be related to an ideal or corrected partition factor R_c by

$$R(x) = \beta + (1 - \alpha - \beta)R_c(x) \tag{6-4}$$

Both short circuit flows are functions of particle size and the short circuit to sinks extrapolates at zero size to the recovery of water to sinks. An exponential dependence with size has been found in a 150 mm dense-medium cyclone.

$$\alpha = R_f e^{-b d_p} \tag{6-5}$$

with $b = 5.43$ mm^{-1} and d_p in mm. Short circuit to floats can usually be neglected except for material smaller than 0.5 mm.

6.2.3 Separation efficiency

The efficiency of separation is specified in terms of the corrected imperfection defined by

$$I_c = \frac{\rho_{25} - \rho_{75}}{2\rho_{50}} = \frac{\text{EPM}}{\rho_{50}} \tag{6-6}$$

where

$$R_c(\rho_{25}) = 0.25 \tag{6-7}$$

and

$$R_c(\rho_{75}) = 0.75 \tag{6-8}$$

The imperfection of the corrected partition curve is independent of the short circuit flows and it is better to base a predictive model on the corrected imperfection than on the imperfection of the actual partition curve.

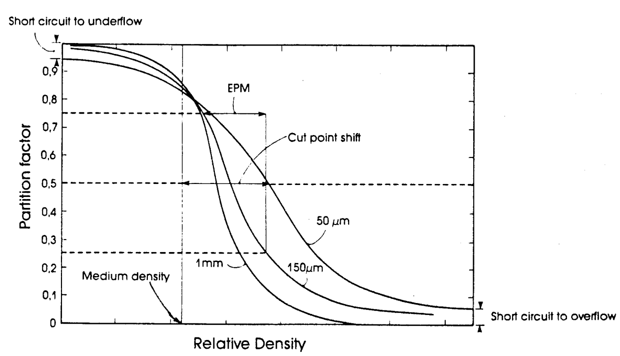

Figure 4-3 *Generalized partition curves for dense-medium separators.*

The imperfection increases as particle size decreases and the partition curves become steadily flatter as particle size decreases as shown in Figure 4.3.

The imperfection also increases as the size of the cyclone increases and for a small (150 mm diameter) cyclone a useful quantitative relationship for the imperfection of the corrected partition curve is

$$I_c - 0.013 = \frac{3.8}{d_p} \tag{6-9}$$

with d_p in µm.

6.2.4 The corrected partition function

A variety of empirical one-parameter expressions for the corrected partition curve has appeared in the literature. These are shown in Table 4.1 as functions of the normalized density $x = \rho/\rho_{50}$. Once a particular function has been chosen to model the corrected partition curve, the actual partition curve can be constructed from the four parameters α, β, ρ_{50} and I_c. It is then a simple matter to calculate the recovery of each particle type to floats and sinks in the separator.

Table 4.1. Empirical equations for the corrected partition function for dense-medium separators. $x = \rho/\rho_{50}$

Type	Function	Relationship between I_c and λ
1	$R(x) = G[\lambda(1 - x)]$	$\lambda I_c = 0.674$
2	$R(x) = 1 - G(\lambda \ln x)$	$I_c = \sinh\left(\frac{0.674}{\lambda}\right)$
3	$R(x) = \frac{1}{1 + \exp(\lambda(x - 1))}$	$\lambda I_c = 1.099$
4	$R(x) = \frac{1}{1 + x^{\lambda}}$	$I_c = \sinh\frac{1.099}{\lambda}$
5	$R(x) = \exp(-0.693x^{\lambda})$	$2I_c = 2^{1/\lambda} - 0.415^{1/\lambda}$
6	$R(x) = 1 - \exp(-0.693x^{-\lambda})$	$2I_c = 2.411^{1/\lambda} - 0.5^{1/\lambda}$
7	$R(x) = \frac{e^{\lambda} - 1}{e^{\lambda} + e^{\lambda x} - 2}$	$2\lambda I_c = \ln\left(\frac{9e^{\lambda} - 6}{e^{\lambda} + 2}\right)$
8	$R(x) = \frac{1}{2} - \frac{1}{\pi}\tan^{-1}(\lambda(x - 1))$	$\lambda I_c = 1.0$
9	$R(x) = \frac{1}{1 + \exp(\lambda(x^{n} - 1))}$	$2I_c = \left(1 + \frac{1.099}{\lambda}\right)^{1/n} - \left(1 - \frac{1.099}{\lambda}\right)^{1/n}$ $2I_c < 2^{1/n}$

The exponential sum function (Type 7 in Table 4.1) has been found to fit data for the dense-medium cyclone well as shown in Figure 4.2

In most large dense-medium vessels handling coarse material, I_c is usually assumed to be independent of particle size. Some representative values are given in Table 4.2.

The nine function types listed in Table 4.1 are shown in graphical form in Figures 4.5

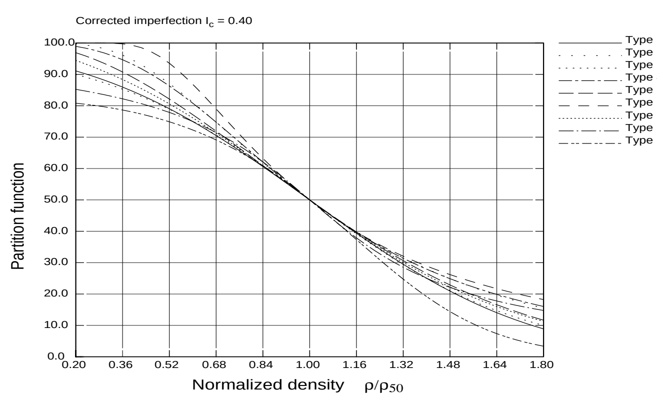

Figure 4-4 *Nine models from table 4.1 for the partition function. All models have the same value of the imperfection* $I_c = 0.4$

and 4.5 to compare their shapes. Although similar to each other, they do exhibit some differences in shape so that one of the functions can fit a particular set of measured experimental data better than the others. When choosing a suitable function to model a particular dense-medium separator the available measured data should be tested against all the functions and the one with the best fit can be chosen.

The functions are plotted with a relatively large imperfection of 0.4 in Figure 4.4. In figure 4.5 the corresponding functions are shown at the lowest practicable imperfection that can be achieved in real equipment namely 0.01. This would represent extremely good separation performance in a dense-medium separator. A probability scale is use for the ordinate in Figure 4.5 to emphasize the differences in shape among the different functions. In this coordinate system the type 1 function in Table 4.1 will plot as a straight line and this is often considered to represent good normal operating behavior. Downward curvature below this straight line in the region $\rho < \rho_{50}$ is taken to indicate less than optimal operation of the dense-medium separator. Positive deviations above the straight line such as those produced by Type 6 model are not usually observed in practice. Type 1 function is the only function in Table 4.1 that is symmetrical about the abscissa value ρ/ρ_{50}. All the others show varying degrees of asymmetry with types 6, 8 and 9 showing the greatest asymmetry.

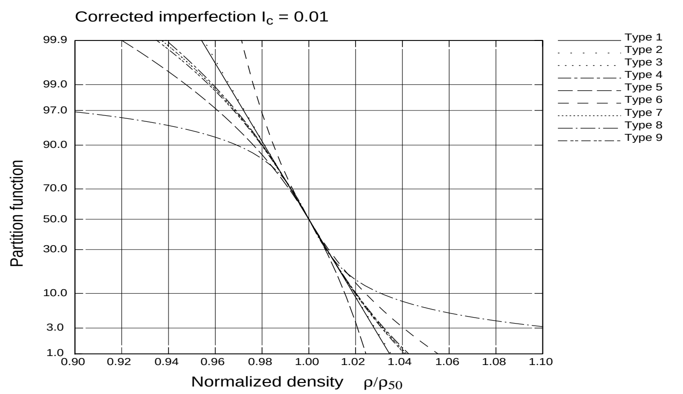

Figure 4-5 *Nine models for the partition function. The ordinate is a probability scale. All models have the same value of the imperfection I_c.*

Table 4.2 Typical values of cut point shift and imperfection for dense medium separators

Separator type	Cut point	Cut point shift	Sp. Gr. differential	Imperfection	Particle size	Reference
Chance cone	1.54 1.37 1.37	 0.033		0.021 0.01 0.03 0.015	 +50mm 12.5×6.5 mm	Leonard 4th ed. FRI
Dense medium vessel	1.41 1.35			0.020 0.018 0.033	 50×25mm 12.5×6.3 mm	Leonard 4th ed
Dense medium cyclone	1.49 1.50 1.51 1.53 1.57			0.019 0.017 0.021 0.025 0.051	½”×⅜” ⅜”×¼” ¼”×8# 8#×14# 14#×28#	SME Handbook p4-19
Dense-medium cyclone	1.325 1.488	0.045 0.142		0.014 0.015	1"×28# 1"×28#	SME Handbook p4-18
Dense-medium cyclone	3.65 3.385	0.59 0.54	0.39 0.51	0.043 0.028	3/16×28# 3/16×28#	Iron ore SME Handbook p4-20
Dense-medium cyclone	3.065 3.095 2.907 3.065	0.455 0.345 0.217 0.215	0.41 0.27 0.28 0.25	0.036 0.045 0.018 0.027	3/16×65# 3/16×65# 3/16×35# 3/16×35#	Chromium ore SME Handbook p4-20
Dense-medium cyclone	2.82 2.4	0.42 0.55	0.41 0.58	0.028 0.037	3/16×28# 3/16×28#	Magnesite Copper ore Davis, Driesen & Oliver

6.3 Generalized Partition Function Models for Gravity Separation Units.

The use of the partition curve is the most widely used method to describe the operation of any gravity separation unit and the generalized partition function was described in section 4.1.1. in connection with dense media separators. It is always possible to describe the operation of any gravity separator by means of a partition function even if the partition function itself depends on the nature of the feed material as is always the case for autogenous gravity separators. In fact the partition curve determined on an operating unit can be used to diagnose the health of the operation. Ideally, partition functions should produce steep symmetric curves that show no short circuiting and thus asymptote to the limits 1.0 and 0.0 at $\rho = 0$ and $\rho = \infty$ respectively. Deviating from the ideal can be attributed to various design and operational inadequacies and Leonard and Leonard (1983) provide a convenient tabulation of causes for poor partition functions in a variety for coal washing units. (J.W. Leonard IV and J.W Leonard, Using Tromp Curves to Diagnose Performance Problems in Coal Cleaning in Basic Mathematics and Computer Techniques for Coal Preparation and Mining. Ed. K.K. Humphreys and J.W. Leonard Marcel Dekker Inc. 1983 pp. 71-79). Although the partition curve is an excellent diagnostic tool it is not entirely satisfactory for simulation because of the difficulty of predicting the partition curve for any particular item of equipment.

A generalized procedure due to Gottfried and Jacobsen attempts to address this problem. (Gottfried B. and Jacobsen S.) The generalized partition curve is estimated in terms of a target specific gravity of separation for the proposed unit. The target specific gravity is the ρ_{50}point on the partition curve plotted as a composite for all sizes. This point is in fact fixed by the size-by-size behavior of the material in the separator and by the size-by-size composition of the feed. In any gravity separation operation, the partition function on a size-by-size basis varies in a systematic manner through the variations in ρ_{50} and the imperfection for each size fraction. This is illustrated for dense medium cyclones in Figure and for the Baum jig in Figure . Both the cut point and the imperfection increase as the size of the particles decrease.

Generalized coordinates are used. The relative size is the ratio of particle size to average particle size in the feed to the unit and the cut point for any size Relative to the effective cut point for the composite material which is the target cut point for the operation as a whole. Once the target specific gravity and the average particle size in the feed are known the cut point and imperfection for each size of particle can be obtained from Figures and . These can be used with any appropriate generalized partition function such as the exponential sum and logistic functions given in equations and . An appropriate amount of short circuiting to either floats or sinks can also be applied if it is anticipated that this kind of inefficiency will be present in the equipment. MODSIM provides the generalized Gottfried-Jacobsen method as an alternative model for most gravity separators.

Osborne (D.G. Osborne coal Preparation Technology Vol. 1 Graham and Trotman Ltd 1988 chapter 8) recommends that the variation of EPM with particle size, equipment size and separation density should be computed using a series of factor

$$\text{EPM} = f_1 f_2 f_3 E_s \qquad (6\text{-}10)$$

f_1 is a factor accounting for the variation of EPM with particle size, f_2 a factor accounting for variation of EPM with equipment size and f_3 a manufacturers guarantee factor usually in the range 1.1 to 1.2. E_s is a standard function representing the variation of EPM with separation density for each type of equipment. E_s for various types of coal washing equipment are

Dense-medium cyclone: $E_s = 0.027\rho_{50} - 0.01$

Dynawhirlpool: $E_s = 0.15\rho_{50} - 0.16$

Dense-medium bath: $E_s = 0.047\rho_{50} - 0.05$

Baum jig: $E_s = 0.78(\rho_{50}(\rho_{50} - 1) + 0.01)$

Water-only cyclone: $E_s = 0.33\rho_{50} - 0.31$

Shaking table and spiral concentrator: $E_s = \rho_{50} - 1$

For dense-medium cyclones f_1 varies from 2 to 0.75 as particle size varies from 0.5 mm to 10 mm.

For dense-medium vessels f_1 varies from 0.5 for coarse coal to 1.4 for small coal.

Because both the Baum jig and the water-only cyclone are autogenous gravity separators, f_1 is dependent on the size distribution and washability of the feed material. For jigs values of f_1 range from 3 to 0.5 as the average size of the feed material varies from 1 mm to 100 mm.