Hydrocyclones for Particle Size Separation

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Introduction

The hydrocyclone is a static, continuous particle size separation device that can also be used for phase separations, including solid–liquid, liquid–liquid and liquid–gas separations and has been used for various classification duties since the 19th century.

Hydrocyclones are attractive for industrial use as they have no moving parts, a small footprint, relatively low capital and operating costs, and are simple to operate. On the other hand, their operation is rather inflexible once installed and single-stage efficiencies may be low, especially for particles finer than 10 μm.

This article describes the mode of operation of hydrocyclones, and the motion of fluid and solid particles in the classifier. Quantifying the separation is followed by the effect of the major design and operating variables on the efficiency.

Two modelling approaches are introduced: a fundamentally based model, including computational fluid dynamics (CFD), and empirical models, which are still in general use.

The article concludes with aspects of further development.

Description

Hydrocyclones are cono-cylindrical in shape, with a tangential feed inlet into the cylindrical section and an outlet at each axis. The outlet at the cylindrical section is called the vortex finder and extends into the cyclone to reduce short-circuit flow directly from the inlet. At the conical end is the second outlet, the spigot. For size separation, both outlets are generally open to the atmosphere. Hydrocyclones are generally operated vertically with the spigot at the lower end, hence the coarse product is called the underflow and the fine product, leaving the vortex finder, the overflow. **Figure 1** schematically shows the principal flow and design features of a typical hydrocyclone: the two vortices, the tangential feed inlet and the axial outlets. Except for the immediate region of the tangential inlet, the fluid motion within the cyclone has radial symmetry. If one or both of the outlets are open to the atmosphere, a low pressure zone causes a gas core along the vertical axis, inside the inner vortex.

The operating principle is simple: the fluid, carrying the suspended particles, enters the cyclone tangentially, spirals downward and produces a centrifugal field in free vortex flow. Larger particles move through the fluid to the outside of the cyclone in a spiral motion, and exit through the spigot with a fraction of the liquid. Due to the limiting area of the spigot, an inner vortex, rotating in the same direction as the outer vortex but flowing upward, is established and leaves the cyclone through the vortex finder, carrying most of the liquid and finer particles with it. If the spigot capacity is exceeded, the air core is closed off and the spigot discharge changes from an umbrella-shaped spray to a 'rope' and a loss of coarse material to the overflow.

The diameter of the cylindrical section is the major variable affecting the size of particle that can be separated, although the outlet diameters can be changed independently to alter the separation achieved. While early workers experimented with cyclones as small as 5 mm diameter, commercial hydrocyclone diameters currently range from 10 mm to 2.5 m, with separating sizes for particles of density 2700 kg m^{-3} of 1.5–300 μm, decreasing with increased particle density. Operating pressure drop ranges from 10 bar for small diameters to 0.5 bar for

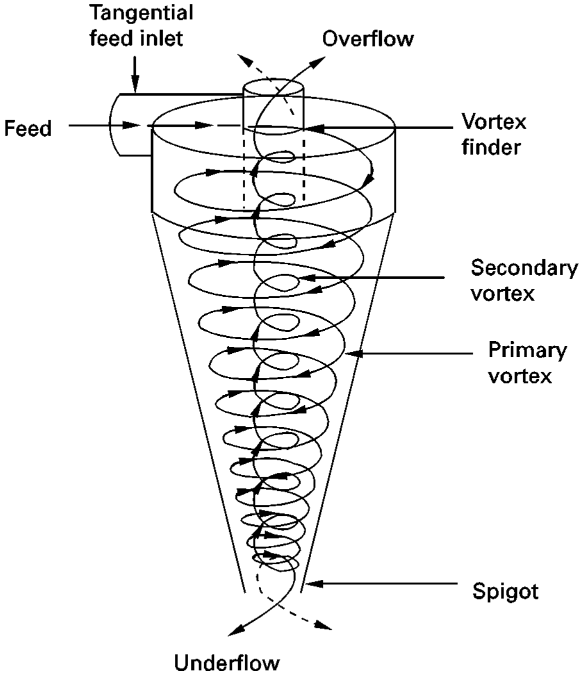

Figure 1 Principal features of the hydrocyclone.

large units. To increase capacity, multiple small hydrocyclones may be manifolded from a single feed line.

Although the principle of operation is simple, many aspects of their operation are still poorly understood, and hydrocyclone selection and prediction for industrial operation are largely empirical.

Liquid Velocity Distributions

Kelsall, in 1952, performed a classic series of experiments measuring axial and tangential fluid velocity profiles in a hydrocyclone using an ingenious experimental system with rotating objectives. The radial velocity was calculated by continuity. The velocity profiles are shown in **Figure 2**. More recently, velocity profiles measured using laser Doppler velocimetry (LDV) were found to correspond closely to those of Kelsall.

The fluid velocity in the cyclone has tangential, axial and radial components. The axial velocity is negative (downward) close to the walls in the cone and positive (upward) near the air core, increasing towards the spigot. This results in a locus of zero vertical velocity between the two vortices, which roughly follows the profile of the cyclone. Toroidal rotation in the inlet flow and interaction between the vortices result in multiple flow reversals.

The tangential velocity increases toward the axis, reaching a maximum near the air core, thereafter decreasing in a forced vortex region. It is the tangential velocity component that generates the centrifugal force, which separates coarser particles from finer ones. The radial velocity, which is two orders of magnitude smaller than the axial or tangential velocities, is directed toward the centre of the cyclone and increases toward the apex.

Particle Motion

Particles entering the cyclone move radially, depending on their mass, either outward due to tangential liquid motion, or inward due to radial fluid motion. In the radial and axial directions, the particle motion is assumed to equal the fluid motion.

Direct measurement of particle motion and solids concentrations at positions in the hydrocyclone can be performed using phase Doppler anemometry. Electrical impedence tomography has been used to measure the position of the air core and the solids concentration profile in a plane through industrial hydrocyclones.

Classification Performance and the Partition Curve

The partition curve (also called a performance curve, efficiency curve or Tromp curve) is used to quantify hydrocyclone particle size separation performance. It quantifies the weight fraction (or percentage) of each particle size fraction in the feed reporting to the underflow product. For any particle size d, the partition number, $p(d)$, is calculated from:

$$p(d) = \frac{U.u(d)}{F.f(d)} \qquad [1]$$

U and F are the mass flow rates of solids (in the same units) and $u(d)$ and $f(d)$ are the weight fractions of particle size d in the feed and underflow streams, respectively. The size at which the partition number equals 0.5 (or 50%) is called the cut size (d_{50}).

A fraction of fine particles always report to the underflow, hence experimentally observed partition curves do not asymptote to zero but to a minimum, called the bypass. This can be interpreted as a fraction of all particles in the feed bypassing classification and reporting directly to the underflow stream. Short-circuiting of feed material to the overflow stream may cause the partition curve not to reach a partition value of 1 (100%): this is not common. The effect of bypass on classification performance is taken into account by correcting the partition value:

$$c(d) = \frac{p(d) - r(d)}{1 - r(d)} \qquad [2]$$

where $c(d)$ is the corrected partition value and $r(d)$ the fraction of material of size d bypassing classification. The particle size at which the corrected partition number is 0.5 (50%) is called the corrected cut size (d_{50c}). It is often found that the bypass equals the water recovery from the feed to the underflow (R_F), although there is no fundamental reason why this should be so.

Figure 3 schematically shows an observed and corrected partition curve.

A so-called fishhook may occur in the observed partition curve when, for particle sizes finer than that at the minimum partition value, progressively higher partition numbers are observed. This is more commonly observed for smaller diameter hydrocyclones and is thought to be the result of turbulent dispersion. In such cases the water recovery may be significantly lower than the lowest partition value observed. Applying the correcting concept to such partition curves is meaningless.

Mathematically Describing the Partition Curve

Corrected partition curves have a sigmoidal shape that can be represented using two-parameter

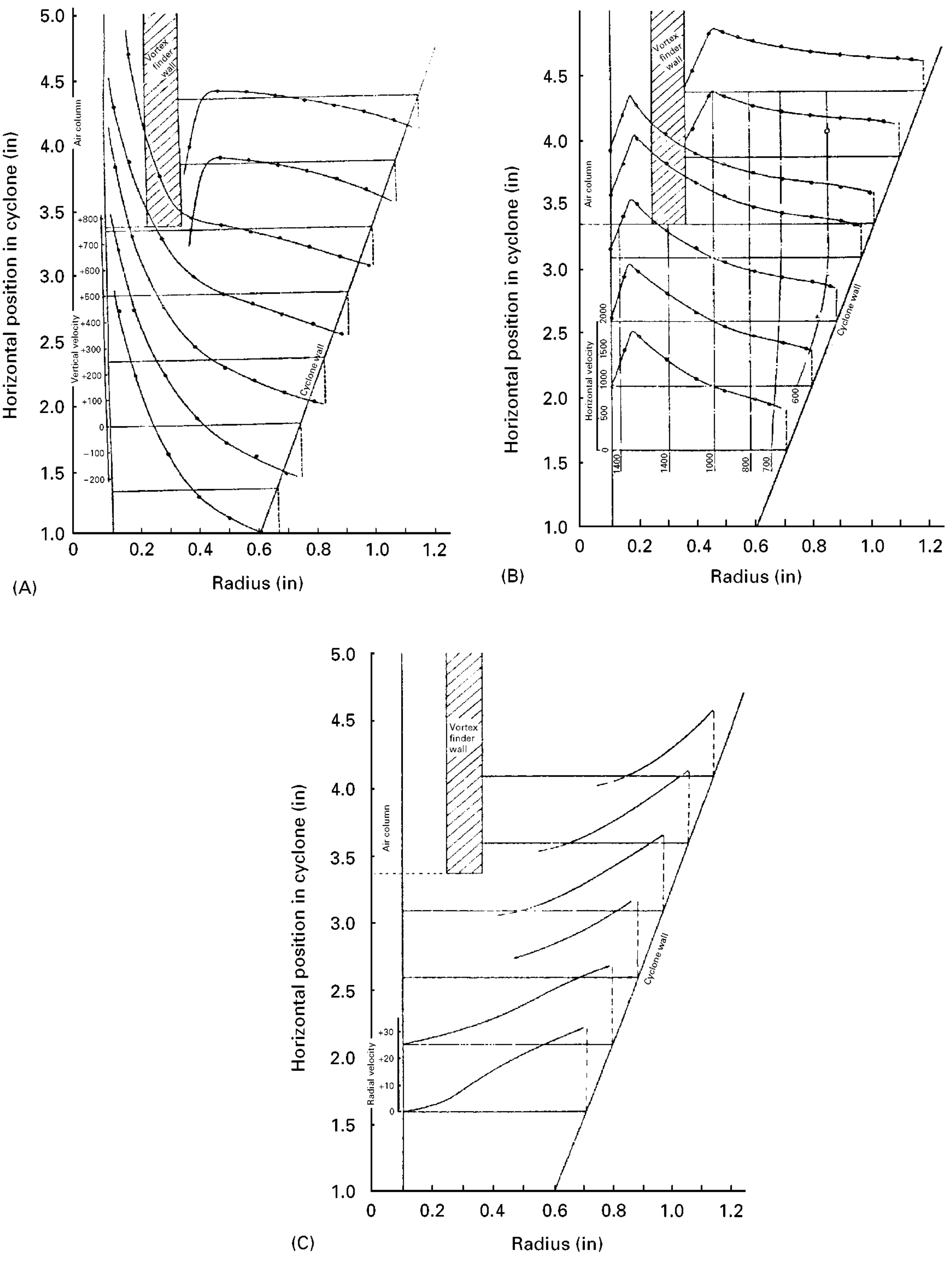

Figure 2 (A) Axial, (B) tangential and (C) radial velocity profiles in a hydrocyclone. (Reproduced with permission from Kelsall (1953).)

functions such as the exponential sum, the Rosin–Rammler and the log-logistic expressions. The two parameters determine the cut size and the sharpness of separation, respectively. The fishhook partition curve can be modelled using the sum of a corrected partition curve and an inverted partition curve multiplied by a bypass fraction.

The observed partition curve gives a complete description of the selective separation of all sizes of solids entering a cyclone and can be used to predict

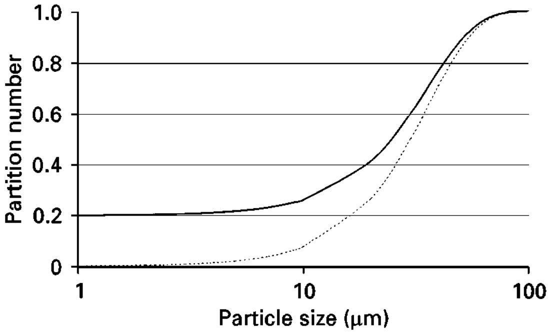

Figure 3 The observed (continuous line) and corrected (dashed line) partition curves of a hydrocyclone with a bypass of 20%.

the product size distribution and solids recovery for changes in feed size distribution. If the bypass is assumed to equal the water recovery, the liquid and volumetric balances can also be estimated.

Hydrocyclone Geometry

The hydrocyclone diameter is the main design variable, and affects both capacity and cut size. The broad operating range available for any hydrocyclone diameter is narrowed down by fixing the inlet and outlet dimensions. It is not generally possible to select independently all the design variables; however, there are reasonable ranges in relation to the hydrocyclone diameter, D_c. **Figure 4** shows the approximate cut size and throughput range that can be achieved using cyclones of different diameters.

The cone angle for classification of hydrocyclones is 15–30°, with smaller angles for finer cut sizes, and larger angles for coarser cut sizes, respectively. The free vortex height is the distance between the bottom of the vortex finder and the spigot. Increasing hydrocyclone height improves both capacity and separation efficiency, and generally varies between 3 and 8 D_c.

The inlet opening is usually rectangular with a height to width ratio of 2 and an equivalent circular diameter of 0.14–0.33 D_c. The inner wall, outer wall or centre of the hydrocyclone inlet may be designed to be tangential to the cyclone body, and may also scroll downwards.

The outlet dimensions are the most important physical parameters used to alter the operation. Vortex finder diameters of 0.13–0.43 D_c are commonly used. Spigot diameters in the range 0.1–0.2 D_c are used, but the ratio to the vortex finder is more important. In general, the vortex finder diameter is greater than that of the spigot. Equal diameters should be avoided.

The Effect of Operating and Design Variables

Table 1 summarizes the effect that changes to the major design and operating variables have on the capacity, cut size and sharpness of classification.

The effect of pressure drop on the sharpness of separation depends on the operating range, as an increase in pressure drop increases the throughput and hence the separation efficiency, but decreases the volumetric flow to the underflow. Of particular interest is the effect of feed solids concentration, which has a significant effect on the classification. **Figure 5** shows clearly that an increase in solids concentration increases the cut size and reduces the sharpness of separation.

Hydrocyclone Models

The modelling of hydrocyclones is performed by either describing the fluid flow and particle motion within the cyclone, or by developing empirical

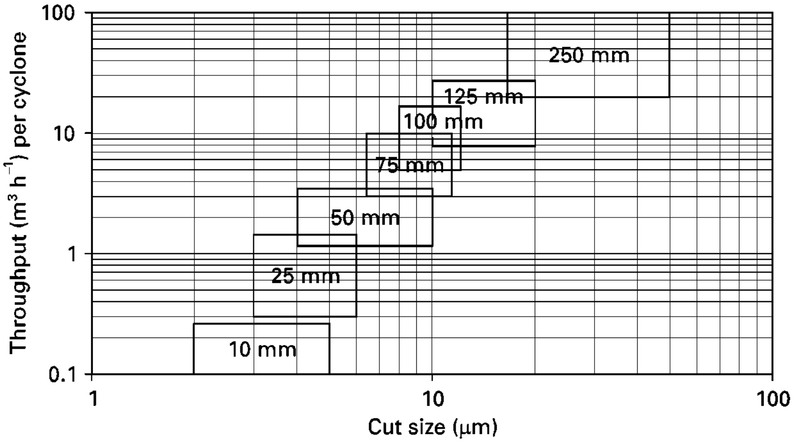

Figure 4 Cut size and throughput for different cyclone diameters.

Table 1 Cyclone design and operating variable effects[a]

Increasing	*Throughput (Q)*	*Cut size (d_{50})*	*Sharpness of classification*
Cyclone diameter, D_c	↑	↑	↑
Vortex finder diameter, D_o	↑	↑	↑
Spigot diameter, D_u	↑	↓	↓
Feed inlet, D_i	↑	↓	↓
Cone angle	Not comparable	↑	↑
Free vortex height, h	↑	↑	↑
Pressure drop, P	↑	↓	↑ or ↓
Volumetric feed solids concentration, ϕ	↑	↑	↓

[a] ↑ increase; ↓ decrease.

(or semi-empirical) relationships between operating variables and measured responses. Fundamental models are appealing from a rigorous standpoint but have difficulty in describing satisfactorily the complex particle–particle and particle–fluid interactions for hydrocyclones operating at higher solids concentrations.

Empirical or semi-empirical models, which relate the parameters of the partition curve to cyclone design and operating variables, are generally used for industrial hydrocyclone modelling and simulation. A number of general models, particularly for larger diameter hydrocyclones, have been developed (see Further Reading).

Fundamentally Based Hydrocyclone Models

Early attempts at understanding the physical principles that govern size separation in hydrocyclones yielded theories based on equilibrium, residence time and crowding. More complete simulations in which fluid and particle motion is estimated from solution of the Navier–Stokes equations have been developed more recently.

Equilibrium orbit theory It can be postulated that particles will find an equilibrium orbit in the hydrocyclone where their terminal settling velocity radially outward is equal to the radial velocity of the liquid inward. A particle will report to the spigot if its equilibrium orbit is in the downward axial liquid flow and to the vortex finder if in the upward axial flow. The cut size is defined by particles that have an equilibrium orbit that coincides with the locus of zero vertical velocity and therefore have an equal probability of reporting to either product streams. An equilibrium orbit may not be achieved due to the short residence times and high solids concentrations in the hydrocyclone.

Residence time theory This theory determines whether the residence time in the hydrocyclone allows a particle entering the cyclone at the centre of the inlet to settle to the cyclone wall and enter the boundary layer flow to the underflow.

Crowding theory At higher feed concentrations, it is found that the separation size is primarily determined by the discharge capacity of the spigot and the feed size distribution. By controlling the outlet dimensions, it is thought that any cut size within the feed size distribution can be obtained.

Computational fluid dynamics (CFD) solutions This is the preferred approach for fundamentally based modelling of hydrocyclone performance. Complete flow modelling of the hydrocyclone

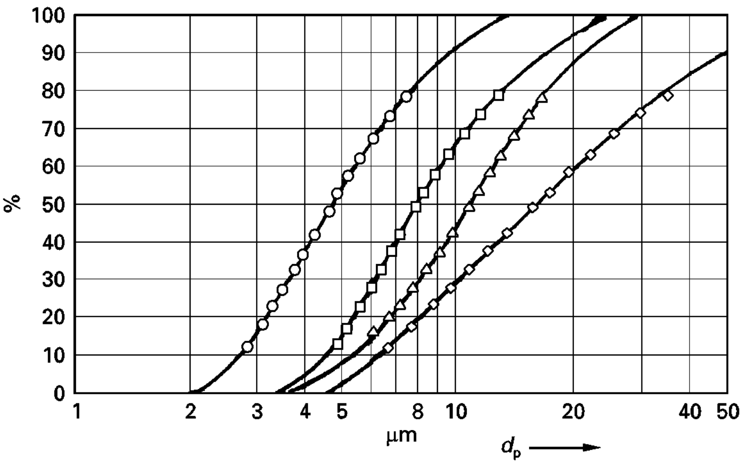

Figure 5 Effect of feed solids concentration on hydrocyclone separation. Circles, 2.68 vol%; squares, 11.11 vol%; triangles, 17.54 vol%; diamonds, 23.75 vol%. (Reproduced with permission from Braun and Bohnet (1989). Copyright: Wiley-VCH.)

involves predicting the liquid-phase velocities, the slurry concentration profile, the turbulent viscosities and the slip velocities of particles with respect to the liquid phase for a range of particle sizes before predicting the partition curve. The solution is complex, because the governing fluid flow equations are nonlinear, simultaneous partial differential equations.

Chakraborti and Miller (1992) have published an extensive review of fluid flow modelling in hydrocyclones. They describe the flow models in detail, giving particular attention to models based on the Navier–Stokes equation and the treatment of fluid turbulence. They further discuss techniques for flow measurement and visualization and give a brief summary of pressure drop correlations and measurements. This paper is an essential reference for the fluid flow modelling approach.

The general approach to develop a complete CFD-based model of a hydrocyclone must include a wide range of components. If it is assumed that variations of local density and viscosity are small for dilute slurries and that particle–particle interactions are negligible, the fluid and particle modelling can be decoupled. Liquid velocities are predicted by combining the fluid transport equations for vorticity, stream function and angular spin velocity with a modified Prandtl mixing length model, which varies both radially and axially, for the turbulent viscosity. The set of simultaneous, nonlinear partial differential equations are solved by overlaying the hydrocyclone dimensions with a rectangular grid and using appropriate boundary conditions at the solid walls and liquid–air interface, to solve for conditions within each cell of the grid. By balancing all the forces on the particle, the particle motion with respect to the fluid can be computed. The particle trajectories are found by calculating axial and radial slip velocities with respect to the fluid. Size classification performance is determined by following a particle of a given size from the inlet until it exits. This computation is repeated for each particle size across the inlet diameter yielding the partition curve.

For concentrated slurries, liquid-phase velocities are affected by local density and viscosity, which in turn are affected by local solid concentration and particle size distribution. Since particle motion determines the concentration and size distribution at each location, this being determined from liquid velocities, an iterative solution is required so that local slurry property changes can be estimated and liquid-phase velocities recalculated.

Advances in CFD methods such as computation grid generation, numerical methods and computing resources are increasing the applicability of this modelling technique to improve designs.

Empirical Models

At present, empirical models are the most commonly used technique for hydrocyclone selection and performance prediction. Empirical hydrocyclone models use the partition curve as a basis for describing size separation. Suitable equations are developed from experimental results to relate the parameters of the corrected partition curve to physical variables. In general, empirical hydrocyclone models consist of four relationships that describe the cut size, the sharpness of separation, the water balance around the hydrocyclone and the throughput–pressure drop relationship.

An empirical hydrocyclone model was described in 1976 that is still commonly used to predict separation performance. This model was the first to document an empirical form for the sharpness of separation and therefore allow direct simulation of expected performance without any testwork. This model form is often used as a basis for the development of models that include further variables, such as, for example, angle of inclination, or for an operating range in which the model has not been tested.

The Rosin–Rammler function describes the reduced partition curve:

$$c_\mathrm{i} = 1 - \exp(-0.693 x_\mathrm{i}^{m}) \qquad [3]$$

where m indicates the sharpness of separation and x_i is:

$$x_\mathrm{i} = \frac{d_\mathrm{i}}{d_\mathrm{50c}} \qquad [4]$$

In SI units, and using the symbols in Table 1, the Plitt equation for the cut size is:

$$d_\mathrm{50c} = \frac{50.5\, D_\mathrm{c}^{0.46}\, D_\mathrm{i}^{0.6}\, D_\mathrm{o}^{1.21} \exp[6.3\phi]}{D_\mathrm{u}^{0.71}\, h^{0.38} Q^{0.45} (\rho_\mathrm{s} - \rho_\mathrm{l})^{0.5}} \qquad [5]$$

where ρ_s, ρ_l and ρ_p are the densities of the solid, liquid and pulp, respectively.

To describe the water balance, Plitt develops a relationship for the volumetric flow split between the overflow and underflow streams, S, rather than the bypass:

$$S = \frac{3.28 (D_\mathrm{u}/D_\mathrm{o})^{3.31} h^{0.54} (D_\mathrm{u}^2 + D_\mathrm{o}^2)^{0.36} \rho_\mathrm{p}^{0.24} \exp[0.54\phi]}{P^{0.24} D_\mathrm{c}^{1.11}} \qquad [6]$$

The relationship for the sharpness of separation is given by:

$$m = 1.94\,\exp[-\,1.58\,R_\mathrm{v}]\left[\frac{D_\mathrm{c}^2 h}{Q}\right]^{0.15} \qquad [7]$$

where R_v, the recovery of slurry to the underflow, is related to the flow split by:

$$R_\mathrm{v} = \frac{S}{1+S} \qquad [8]$$

The relationship between the pressure drop across the cyclone and the throughput is given by:

$$P = \frac{1.88\,Q^{1.78}\exp[0.55\phi]}{D_\mathrm{c}^{0.37}\,D_\mathrm{i}^{0.94}\,h^{0.28}(D_\mathrm{u}^2 + D_\mathrm{o}^2)^{0.87}} \qquad [9]$$

Roping is affected by the spigot diameter and the volumetric solids concentration in the underflow; however, there is no satisfactory method for predicting operating limit.

It must be emphasized that empirical models, although developed from an extensive database, should be used with caution.

Future Developments

The extremely wide range of hydrocyclones available and separation applications for which they can be used assures their future role in particle classification. However, significant obstacles remain before they can be used to replace more efficient methods for fine classification purposes, such as centrifuges. Classification inefficiencies, in particular the large bypass, limit their application. The potential of very small diameter hydrocyclones for sub-micron particle separation, especially in multistage configuration, is enormous, if these inefficiencies can be reduced.

Hydrocyclone modelling has advanced significantly with the use of CFD. Empirical hydrocyclone models are convenient ways of describing experimental data but do not enhance the understanding of the separation and CFD models will play a greater role in hydrocyclone simulation. Nonintrusive measurement techniques such as laser Doppler anemometry (LDA), laser Doppler velocimetry (LDV) and tomography have indicated the source of hydrocyclone inefficiencies. With increased resolution and combined with CFD models, this will improve hydrocyclone unit design.

Hydrocyclone operations will benefit from novel methods for monitoring which are currently being developed. Industrial tomography is becoming affordable, and the potential of visual and sonic techniques has been illustrated.

See also: **II/Particle Size Separation:** Electrostatic Precipitation.

Further Reading

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Instrumentation of Field Flow Fractionation

See **II / PARTICLE SIZE SEPARATION / Theory and Instrumentation of Field Flow Fractionation**

Sedimentation

See **II / PARTICLE SIZE SEPARATION / Split Flow Thin Cell (SPLITT) Separation**