Testing of hydrocyclones: methods available and decisions to make

Pozvánka na přednášku

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Testing of hydrocyclones: methods available and decisions to make,

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Abstract

Recent advances in hydrocyclone modelling and scale-up may often obviate the need for testing prior to process design but in particularly challenging applications when small diameter units are needed (such as in wheat starch processing), testing of specific cyclone geometries at high feed solids concentrations is still required. Also, the need for testing is always great in research and in the newly-emerging applications such as in the petrochemical (especially in off-shore and deep sea processing), food or biological separations, and in de-oiling or de-gassing of liquids. Historically such testing was a tedious and time-consuming task but modern instrumentation and computer control have much simplified it. This paper reviews the methods available and the important decisions that have to be made with respect to the test rig, the choice of the test suspension, the sampling scheme and the operating conditions to be used. The paper will be of interest to all practitioners such as chemists, process engineers or plant operators, as well as students and academics.

The paper text below is based on an extract from the new book co-authored by the speaker (**Hydrocyclones Volume II by L Svarovsky and G Svarovsky, 2013**), with the section and figure numbers preserved here as they appear in the book. The book itself is available from www.svarovsky.org/fps2.

Introduction

The separation performance of a conventional hydrocyclone depicted below is particle size-dependent. At low concentrations in the feed and for granular or near-spherical solids, this performance can be predicted from available models and digital flow simulations. At high feed concentrations or for unusual slurries/particles it is still necessary to carry out testing of specific hydrocyclone geometries at different operating conditions.

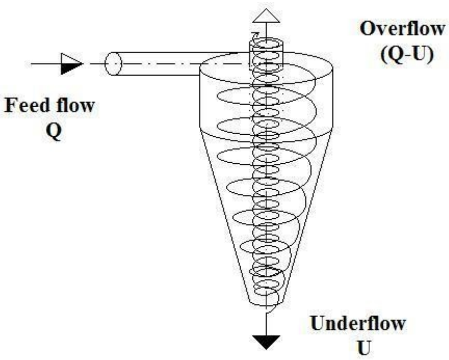

Figure A3.1: Schematic diagram of a hydrocyclone and of the vortex inside it. Flow rates Q, U and Q-U represent total volumetric flows in the three streams shown

Such testing involves not only measurement of flow rates and solids concentrations in two of the three streams around the operating hydrocyclone but also of particle size distributions in those streams. The measurements are done either on-line or off-line and in either case it is an expensive and technically demanding exercise. Here are some rules and recommendations for such test work (applicable also to any other dynamic particle separators such as sedimenting centrifuges), starting with the test rigs.

4.1.5 Test rigs

Setting up a test rig for hydrocyclone testing is a relatively simple task, providing some basic recommendations are observed. The notes here are concerned only with the components of the test rig—the choice of the test suspension is dealt with in Section 4.1.5.

Figure 4.2 shows a schematic diagram of a re-circulation test rig most frequently used, with all important elements in it shown in general terms. The feed slurry is pumped from the feed tank into the cyclone. It is good practice to protect the pump from coarse foreign particles or objects fallen into the feed tank by placing a coarse mesh over the outlet point in the tank.

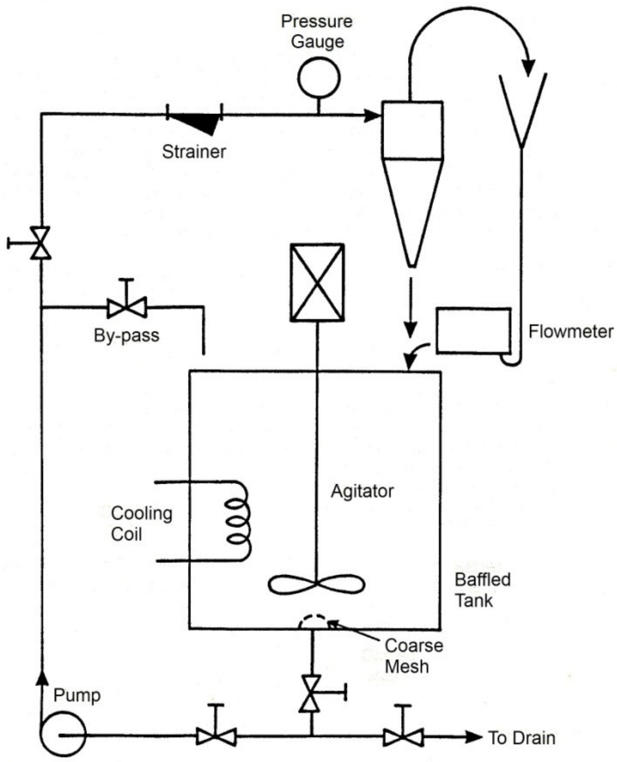

Figure 4.2: A conventional recirculation test rig containing essential elements

A by-pass line is usually provided in most test rigs which takes the pumped suspension back into the feed vessel, to facilitate gradual start-up and easy control of the circuit. During a test the amount of by-pass should be preferably minimal or none, because some separation may take place in the T-piece used for splitting the flow and this may introduce a bias in the size distribution actually entering the cyclone.

If the pressure needs to be varied for some reason, the control of pressure drop across the cyclone can be achieved with a throttle valve placed in the cyclone feed pipework. However, a preferred way is to use a speed controller on the pump. A pressure gauge is used in the cyclone feed line, close to cyclone inlet (usually about one pipe diameter before the inlet connection), to measure the inlet pressure.

Once again, the simplest way to keep a balance between the overflow and underflow pressures is to discharge both of the streams into the atmosphere, and this is the way most test rigs are set up. Atmospheric pressure provides steady and equal back pressure on both outlets and, furthermore, a free-discharging underflow can be easily observed and sampled.

It is usual in test rigs to measure the flowrates in the two outgoing streams, the underflow and overflow. The problem is that both of these streams have air entrained in them and some common flowmeters like the rotameter cannot be used without adequate de-aeration of the flow prior to the measurement. The underflow presents little problems here because the 'bucket and stopwatch' method can be used there, up to total rig flowrates of about $20m^3/h$ or higher. The overflow may be conveniently and cheaply measured with a V-notch type weir box as frequently used in the water industry. It provides de-aeration and its calibration is independent of the viscosity of the fluid. Another alternative is the magnetic flowmeter.

Suitable sampling systems might be built into larger rigs to allow samples to be taken simultaneously from the two outgoing streams for measurement of solids concentrations and particle size distributions. **The sampling should be simultaneous and of the same duration in both of the streams** in order that the remaining feed suspension in the systems will be unchanged in its particle size distribution. Sampling from the feed vessel is not recommended because particle stratification and settling takes place there and the actual feed solids concentration and size distribution are best reconstructed from the measurements on the two outgoing streams (as mass balance must apply under steady-state operation).

The outgoing streams (and the feed stream too) may also be equipped with solid concentration or solid mass flow measurement. Gamma radiation density gauges or vibrating U-tube densitometers have been successfully used for this purpose.

The feed tank should be agitated with a variable speed agitator (some smaller rigs can get away with using no agitators by relying on the turbulence of the incoming streams in vessels of suitable shape) and provided with baffles to break the vortex inside the vessel which would lead to severe stratification of particles. **Installation of a cooling coil inside the feed vessel is highly recommended** (as indicated in Figure 4.2) because the temperature of the slurry can rise significantly during an experiment due to the friction losses in the continuous recirculation.

4.3.1 Conventional testing for grade efficiency and cut size

Testing the grade efficiencies of hydrocyclones is a tedious and time-consuming task. It is still very much needed, however, particularly when investigating the effect of feed concentration of solids where the available models still require experimentally-determined constants. As to the equipment, the usual method is to install the hydrocyclone in a recirculation test rig (see Figure 4.2 for a schematic diagram) described in Section 4.1.5. Such dedicated test rig allows full control of the test conditions and a free choice of the feed suspension and its properties. The off-line test rig can also be well instrumented and provided with extra power, water and space for taking samples etc. However, it is perfectly feasible and in some cases advantageous (but still rarely practiced) to test hydrocyclones in situ and on-line, while installed and operating in a process. In spite of the IT revolution this century, there still persists some reluctance to install extra instrumentation on plants, and off-line testing is therefore still more-or-less the norm.

The first important decision in off-line hydrocyclone testing for grade efficiency curves and cut sizes is the choice of **the test suspension**. For recirculation test rigs like the one shown schematically in Figure 4.2 it is clearly imperative that the suspension should be stable long-term, with minimum of attrition and/or thermal deterioration of the particles. For hydrocyclones intended for specialist slurries it is of course best to use the targeted material but, as possible bacterial growth in biological slurries or in crude oil might be a problem, suitable inert substitutes are sometimes necessary. For general use hydrocyclones, a stable and easily-dispersible material is usually chosen, with particles of near-spherical or at least granular shape. In testing gas cleaners, many test materials are described by various international standards but for hydrocyclone testing this area is much less regulated or standardized. Granular sand of various grades suspended in water is usually the preferred choice for testing larger diameter hydrocyclones and most hydrocyclone manufacturers for that reason most often present their test results for sand density of 2600kg/m^3 in water at 20°C. For testing small diameter cyclones, superfine grades of material a lot finer than granular sand are needed and limestone or chalk are often the preferred choice. The additional advantage is that the disposal of these often difficult-to-dewater, colloidal test slurries is not much of a problem due to their inert nature, maybe even beneficial to waste water treatment plants.

Whatever the chemical nature of the eventual test slurry chosen, it must be well characterized for particle size distribution, density, particle shape, liquid density and viscosity (the liquid should of course be normally Newtonian). And the stability of these properties with time has to be checked during the test programme. **The grade of particle size of the feed slurry should be carefully chosen with regard to the range of cut size expected from the hydrocyclone under test.** No need to choose mono-disperse or near-mono-disperse materials: a polydisperse material is best, with the range of particle sizes present well-covering the range of cut size expected from the tests; and not much wider than that range because there is little point in feeding to the hydrocyclone large amounts of solids which are either too fine to separate much at all or too coarse to give any less than near-100% efficiency under all test conditions. The latter case is more commonly encountered. We have seen countless cases of test work in industry when in excess of 70% or more of the test particles (by mass) is far too coarse to participate in testing the grade efficiency and these particles thus swamp the gravimetric measurements of concentration and particle size. So much so that the measurement errors for the material actually probing the 'inefficiency' of the hydrocyclone at finer particle sizes below 100% recovery are so great that they make the whole expensive exercise practically worthless.

As a rule-of-thumb, **the median or arithmetic/geometric mean size of the particle size distribution in the feed should lie within the range of cut size expected from the tests**. This should be reflected in the test results in that the **total efficiency (recovery) by mass in most of the tests should not be very far from 50%**. If the total recoveries range higher than say 80%, such tests are likely to be worthless and a finer grade material should be sought.

As to the back pressures imposed on the two outlet streams, they are normally equal and usually atmospheric in that both the overflow and underflow are discharged into open vessels. Such operation of hydrocyclones is referred to as balanced and all theories and models in Chapter 3 apply to it. If either of the streams is subjected to back pressure of any kind, the test performance will be affected unless the other stream is controlled to compensate for this to bring the two pressures back into balance. A vast majority of off-line testing is done under balanced conditions with only a few exceptions in very specialized applications.

The conventional test method requires sampling of at least two of the material streams involved, followed by full particle size analyses (and concentration measurements) of these samples and, also, by flowrate measurements for the necessary determination of the total solids recovery to underflow. The total solids recovery may alternatively be evaluated from the particle size distribution of the third stream. As to the selection of the combination of material streams chosen for the testing, the reader is referred to Chapter 2 of the first volume of this book (Ref. 1, p.17).

For any separator with a size-dependent performance, such as a hydrocyclone, the grade efficiency varies with particle size, and a graphical representation of this is called the grade efficiency curve. As the value of the grade efficiency has the character of probability, it is sometimes referred to as the partition probability; the curve then becomes the partition probability curve or Tromp curve.

In practice, the grade efficiency curve is a continuous function of particle size *x*—see Figure 4.3 which gives a typical actual grade efficiency curve for a hydrocyclone. The preferred definition of particle size in grade efficiency testing of hydrocyclones is the Stokes' diameter as measured by laboratory methods involving gravitational or centrifugal sedimentation. This takes care of the effects of particle density, shape and fluid viscosity on particle-fluid interaction, within the validity of Stokes' Law.

The effect of flow splitting (or 'dead flux') in applications with appreciable underflow, as is common with hydrocyclones, is to modify the shape of the grade efficiency curve making it appear as if the performance of the hydrocyclone were better than it actually is. The actual grade efficiency curve in Figure 4.3 does not start from the origin (as it should for inertial separation) but has an intercept, the value of which is usually equal to the underflow-to-throughput ratio (or the 'flow ratio') R_f. This is because the very fine particles simply follow the flow and are split between the underflow and the overflow in the same ratio as the suspension flows. **The R_f ratio is defined as** the fraction of the volumetric feed rate which turns up in the underflow, i.e. the **total underflow volumetric rate divided by the total feed volumetric rate**. We stress the word 'total' here, because we mean the whole volumes of the respective suspensions and not just the liquid volumes within them (excluding the solids). This is because superfine particles turn up in the underflow at rates a little greater than would correspond to them being evenly distributed in the suspending liquid only—some are swept in by the coarse particles in proportions roughly as if they were distributed in the whole volume, including the solids.

Some mineral processing authors and researchers still rigidly define R_f as ratio of liquid flows only but this is not only an unnecessary complication in calculations for the sake of a very small difference but our much simpler definition actually correlates better (Ref. 6) against the intercepts determined by measurement (see Figure 4.3 and the notes about the fish-hook later in this section). Notwithstanding the fact that particle size measurement can never take us down to zero particle size, the intercept can never be measured directly but only deduced from the G(x) curve by extrapolation. However, our modern measurement methods can now take us well into the sub-micron region, very much closer to zero particle size than was possible at the time of the original foundation work.

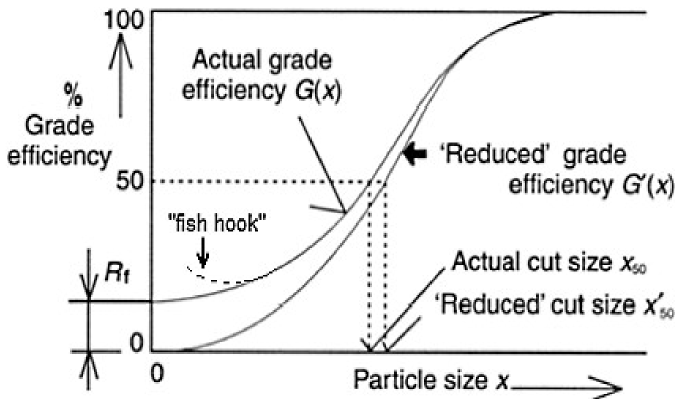

Figure 4.3: Grade efficiency curves for a hydrocyclone. The measured actual curve sometimes exhibits the so-called 'fish hook effect' (dashed curve) when it rises above the value of R_f at the fine particle end.

In order to remove the effect of flow splitting from the efficiency definition so that it describes only the true 'centrifugal efficiency', the grade efficiency is 'reduced' by the following equation (Ref. 1, 3):

$$G'(x) = \frac{G(x) - R_f}{1 - R_f} \qquad (4.1)$$

This usually forces the curve to pass through the origin as indicated by the second curve, G'(x), in Figure 4.3. The reduced grade efficiency curve can, for some separators, be approximated by an analytical expression such as the one used in this method—see Equation 4.2 in the following section.

In practice, the very fine particles sometimes show up in the underflow at proportions somewhat greater than predicted by the splitting of the flow, and the grade efficiency may exhibit the so called 'fish hook effect' indicated by a dashed curve in Figure 4.3. This is due to physical effects that have nothing to do with the centrifugal separation process in a hydrocyclone and, consequently, the effect does not scale-up in the same way. Therefore in testing hydrocyclones for actual cut size it is best either to try and prevent the effect from taking place, such as by adding dispersant or, if nothing works, simply ignore the effect and connect the curve to the R_f intercept on the Y-axis. As it happens, things usually do appear as indicated in Figure 4.5 where the curve coming down from the coarser end does tend towards the value of R_f and it is only for the finest fractions when it starts to lift higher. In hydrocyclone design and in the development of the models for it, the fish hook phenomenon does not affect the cut size correlations and is now well recognized to be an unimportant 'placebo effect'. In operations such as thickening, clarification or any solids recovery, the small extra recovery of fines due to the fish hook effect is beneficial and there is no reason to remove or suppress it. In classification of solids by particle size, however, the effect is highly undesirable as it drags more fines into the coarse product or at least it reduces the yield of the fine product.

As to the reasons for the fish hook effect, there have been some studies in the literature but sometimes the fine particles are simply flocculated together, or onto the surface of the larger ones, and adding a small quantity of a dispersant bears witness to this as it often removes or at least reduces the effect. The reason it shows up in our results is because when analysing the samples for particle size, the flocs are usually dispersed by ultrasound or dispersant, and the superfine particles appear at finer sizes than the floc size in which they passed through the hydrocyclone. The second possible reason for the effect is that superfine particles are dragged by the wakes generated behind larger particles and swept into the underflow in greater proportions than expected from the flow split. This phenomenon is well known and observed in gravity settling and it takes place even on molecular level: in a binary mixture of gases passing through a polymer membrane the two different sizes of molecules affect each other's permeability. We have added a bibliography section on the effect at the end of this chapter so that any interested readers can follow this up. However not only is the effect a 'placebo' in its lack of importance in hydrocyclone modelling and design, but so are most of the published papers about it.

The grade efficiency curve, while it provides the most comprehensive description of separation efficiency, is rather clumsy for correlation with operating variables or for simple equipment comparisons. Such applications call for a single number, independent of the size of the feed solids, as a measure of efficiency.

This is available in the form of the 'cut size' x_{50} which is defined as the size corresponding to 50% on the grade efficiency curve G(x)—see Figure 4.3. Most mathematical descriptions of the performance of hydrocyclones, however, are in terms of the reduced cut size x'_{50} also shown in Figure 4.5 and defined as the size corresponding to 50% on the **reduced** grade efficiency curve G'(x).

The complexity and cost of determining the full grade efficiency curve can be avoided if only the cut size is sought. The alternative, direct ways of determining the cut size are described in Chapter 2, pp. 23-26, of the first volume of this book (Ref. 1). Our new method in Section 4.3.2 below also evaluates primarily just the cut size but also gives a measure of the sharpness of cut.

The grade efficiency curves evaluated from conventional tests are subject to large measurement errors because all constituent errors of sampling, particle size measurements and concentration measurements are propagated into the final result. It therefore makes sense to reduce, if possible, the number of measured variables that are needed. In our on-going search for new methods of on-line particle size analysis and in developing one based on a hydrocyclone, we have discovered an elegant way of simplifying the grade efficiency testing which also, at the same time, gives more reproducible results than the conventional tests. The theory and an example of use of the new test method are given in the following.

4.3.2 A new method of testing hydrocyclones, Ref. 7

This section describes a new and simple experimental method for obtaining the reduced cut size and the geometric standard deviation of the reduced grade efficiency curve of an operating hydrocyclone. The method relies on feeding a known and fully-characterised slurry to the hydrocyclone under test, and on measuring only two solids concentrations (in the feed and in the overflow), one static pressure differential and the slurry temperature. These measurements are best done and logged by a personal computer, and have to be repeated at two different pressure settings.

The new method eliminates the need for sampling, particle size determinations (except that of the feed suspension but this is only done once for a whole string of experiments) or flowrate measurements. This makes the tests simpler than the conventional test methods and also capable of being performed by simple, on-line instrumentation under computer control. A well-known petrochemical company has recently adopted the method for testing de-sanding hydrocyclones.

The underlying theory is fully developed in this section, together with its application to a specific case of testing a small diameter hydrocyclone for later use in monitoring of very fine particle size in industrial slurries.

4.3.2.1 The theory

As the separation process has a random nature, the reduced grade efficiency curves of hydrocyclones can often be fitted by a cumulative log-normal function in the following form (Ref. 3, Equation 3.51 on page 95):

$$G'(x) = 0.5 + 0.5 erf\left[\frac{\ln(x) - \ln(x'_{50})}{\sqrt{2}\ln(\sigma_s)}\right] \qquad (4.2)$$

where the erf function is defined as:

$$erf(z) = \frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2} dt \qquad (4.3)$$

and erf(z) can be evaluated using tables, series or analytical approximations. Note that x'_{50} and σ_s can be determined from a plot of the reduced grade efficiency curve in a log-probability graph paper or by using a curve-fitting package such as the one in Ref. 8.

Once the actual grade efficiency curve is known for a given set of operating conditions, the total efficiency E_T (recovery of solids into the underflow) expected with a particular feed of a cumulative particle size distribution F(x) can be predicted using the following relationship:

$$E_T = \int_0^1 G(x).dF \tag{4.4}$$

Total efficiency E_T can also be reduced to account for the splitting of the flow in analogy with Equation 4.1, i.e.

$$E'_T = \frac{E_T - R_f}{1 - R_f} \tag{4.5}$$

Note that an equation similar to Equation 4.4 applies to the reduced efficiencies, i.e.

$$E'_T = \int_0^1 G'(x).dF \tag{4.6}$$

According to the present method, the particle size distribution of the feed solids must be capable of being closely approximated by the log-normal distribution in the following form, analogous to Equation 4.2 (as cumulative fraction undersize):

$$F(x) = 0.5 + 0.5erf\left[\frac{\ln(x) - \ln(x_g)}{\sqrt{2}\ln(\sigma_g)}\right] \tag{4.7}$$

where the erf function is again defined in Equation 4.3. The above mentioned assumption means above all that the feed suspension must be **mono-modal** and, secondly, that it was generated in a randomized process and therefore well fits the above log-probability function. This is not a problem because the test solids are a matter of choice in off-line testing, hence the solids are selected to suit this requirement.

The total reduced efficiency E'_T can then be predicted from $G'(x)$ and $F(x)$ by integration (Equation 4.6) and this, using Equations 4.2 and 4.7 leads to the following formula (Ref. 3, Equation 3.25, p.83):

$$E'_T = 0.5 + 0.5erf\left[\frac{\ln(x_g) - \ln(x'_{50})}{\sqrt{2}\sqrt{\ln^2(\sigma_g) + \ln^2(\sigma_s)}}\right] \tag{4.8}$$

The total reduced efficiency E'_T can also be evaluated directly from the feed solids concentration c and the solids concentration in the overflow c_o using another formula (Ref. 3, Equation 3.43, p.90):

$$E'_T = 1 - \frac{c_o}{c} \tag{4.9}$$

Note that, conveniently, Equation 4.9 does not require the knowledge of the flow ratio R_f. The combination of equations 4.8 and 4.9, by eliminating E'_T, forms the basis of the present method:

$$1 - \frac{c_o}{c} = 0.5 + 0.5erf\left[\frac{\ln(x_g) - \ln(x'_{50})}{\sqrt{2}\sqrt{\ln^2(\sigma_g) + \ln^2(\sigma_s)}}\right] \tag{4.10}$$

In the above Equation 4.10, the response of the separator to the operating conditions, in terms of the cut size x'_{50} and the standard geometric deviation of the reduced grade efficiency σ_s, can be found experimentally by using a feed of a known particle size distribution described by Equation 4.7 above and by monitoring the two concentrations c and c_o.

As one equation is not enough for calculating the two parameters, another equation has to be generated. This is done by changing the operating conditions whilst feeding the separator with the same slurry. With hydrocyclones, for example, Equation 4.10 can be duplicated by taking measurements at two different pressure drops but, as the cut size changes with pressure drop, a fundamental model describing such change also has to be available. It is also assumed here that the value of σ_s does not change with a small change in pressure drop.

One such equation linking the reduced cut sizes at two pressure drops close together is the fourth-root proportionality quoted in Equation 6.10 in the first volume, Ref. 1, p.95 reproduced here:

$$x'_{50} \sim \sqrt[4]{1/\Delta p} \qquad (4.10a)$$

This is because the dependence of Eu on Re is weak and Eu can be assumed constant between close pressure drops, thus making the pressure drop-flowrate relationship quadratic. And if Eu is constant, so is Stk'_{50} because $Stk'_{50}.Eu$ = const according to the simple theories in Section 3.1, and the definitions in equations 4.12 and 4.13 lead to the simple relationship in Equation 4.10a.

4.3.2.2 Practical use of the method

The sequence of the measurement, preferably controlled by a computer, is to take the readings of c and c_o at one pressure drop (result set 1), then switch to another pressure drop and repeat the measurement (set 2). Figure 4.4 shows a schematic diagram of the measurement positions, with all of the readings being capable of being taken and logged by a computer. The concentration readings are from two separate and suitably calibrated densitometers such as gamma gauges, vibrating U-tube density meters or ultrasonic devices.

It is also possible to use just one densitometer (as we had done, Ref. 7) and re-route periodically and alternately the feed and overflow streams through it. This is best done by solenoid or motorized valves, controlled by the computer (see an example in Figure 4.5 described below).

The evaluation of results is done with a computer which uses a mathematical model of the separator function and the following simple algorithm for the evaluation of the two parameters x'_{50} and σ_s:

1. Assume σ_s and evaluate $(x'_{50})_1$ from Equation 4.10 and the result set 1;
2. change Δp and calculate $(x'_{50})_2$ from the result set 2;
3. use a fundamental model which should link the two values of x'_{50} (Equation 4.10a) and if it does not, keep changing σ_s and re-calculating the two values of x'_{50} until it does;
4. print or display the two final values of x'_{50}, each corresponding to a different pressure drop, and the one common value of σ_s.

Given the simplicity of the above calculations and the speed of personal computers, the calculations are done virtually instantaneously. The only delay in the measurement is through the necessity of switching to another pressure drop and the need to establish steady-state operation after the change. This is, however, quite short (a few seconds) in hydrocyclones. (Note that the establishment of steady state operation is determined by computer and no readings are logged until they stabilize.)

According to the present test method, the feed slurry containing the test solids is recirculated through a specially built and instrumented test rig (containing the hydrocyclone under test) such as the one shown schematically in Figure 4.7 and further described in the following section. The small step change in pressure drop required can be easily introduced by using a solenoid or motorised valve, or by changing the speed of the supply pump, with the change initiated by the controlling computer.

The only particle size analysis required by the present method is that of the test solids in the feed stream, and this is done off-line with laboratory analytical equipment and repeated many times to reduce measurement errors.

4.3.2.3 Experimental apparatus

In the experimental rig shown in Figure 4.5 (see Ref. 7), which we used to test a 10mm stainless steel 'Doxie' hydrocyclone from Dorr-Oliver, the change from one operating pressure to another is achieved by switching on or off the solenoid valve (sv) in the by-pass line 1. This is, however, only possible when the test solids contain only fine particles which do not separate significantly in the T-junction 2 which splits the pumped flow into the hydrocyclone feed line 3 and the by-pass line 1. In the case of coarser slurries used in testing larger hydrocyclones, this arrangement would not be acceptable and the change in the operating pressure drop might better be achieved by changing the speed of the supply pump. Much the same applies to the two continuous samples here simply bled off the feed and overflow lines. With coarser test suspensions, the samples would have to be withdrawn isokinetically to avoid bias in the test results.

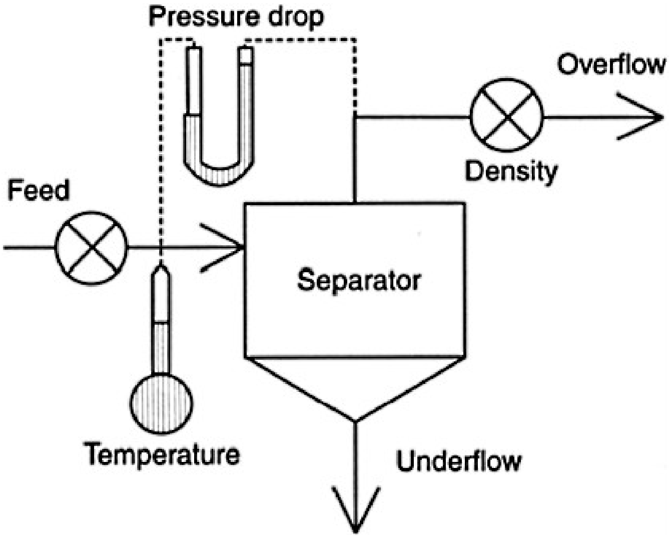

Figure 4.4: A schematic diagram of the measurement positions

It may also be noted from Figure 4.5 that, in this example, only one densitometer was used and the two streams to be measured, the sample stream 4 from the feed stream 3 and the sample stream 5 from the overflow 6, were switched through it alternately, with a delay in between to allow each sample stream to reach the sensor head of the instrument. A vibrating U-tube density meter by Anton Paar was used in the example. Note also that both of the streams taken through the densitometer have to be well de-aerated and this is achieved by venting the lines and routing them in such a way that de-aeration takes place in inclined flow by gravity.

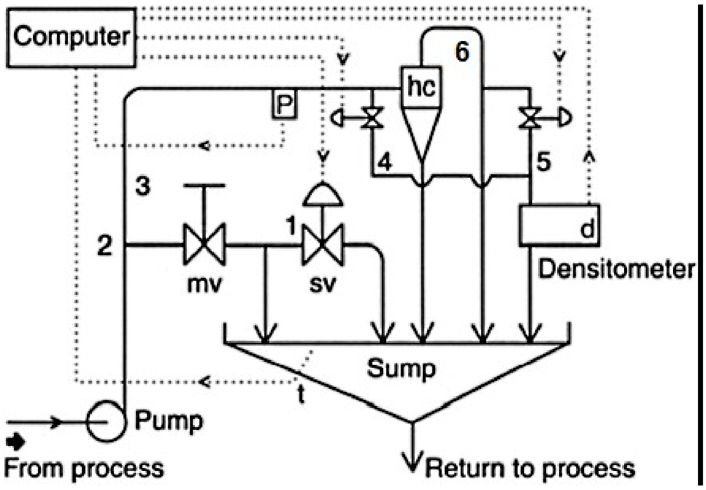

Figure 4.5: A schematic diagram of the experimental setup where d is density measurement (vibrating u-tube), p is pressure drop measurement (piezo-electric), t is temperature measurement (thermocouple), hc is hydrocyclone, mv is manual valve, sv is solenoid valve

4.3.2.4 Example of test results

Figure 4.6 shows the particle size distribution, by mass, of the solids used in the tests (chalk), as obtained with the combination of the Ladal Pipette Centrifuge and the Andreasen Pipette Method (Ref. 7). As can be seen from the linear shape of the log-probability plot, the distribution is very nearly log-normal and thus suitable for using the new test method. Furthermore, the median size of the chalk (3.9 microns) is within the range of cut sizes expected from the hydrocyclone (2 to 5 microns) which is a requirement for effective separator testing—see Section 4.3.1.

The most important effect to be tested in hydrocyclones is that on the feed solids concentration. In Ref. 7 the range to be covered was from 0 to 20% by volume. A personal computer was used to control the rig and log the data, using specially-developed software which included the necessary algorithms listed previously.

Besides the feed solids concentration c, there is a whole host of variables affecting hydrocyclone performance and these are conveniently grouped together in dimensionless groups. A model based on the use of such groups has been published before (see Ref. 1 or Chapter 3 in this book) and the present method is based on an adaptation of this model to small diameter hydrocyclones.

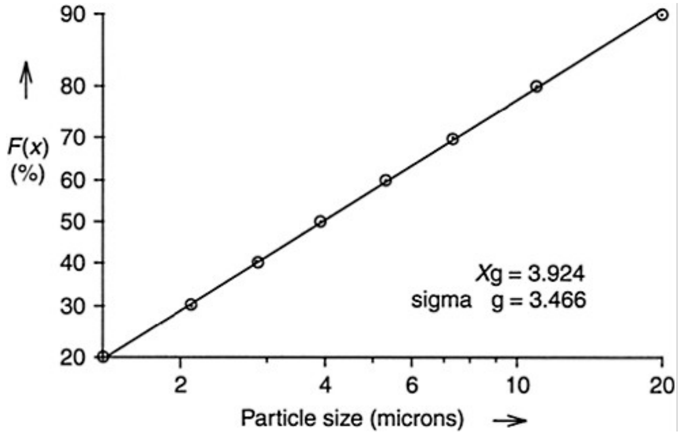

Figure 4.6: Particle size distribution by mass of the test powder (chalk).

Whilst with larger hydrocyclones the resistance coefficient called the Euler number Eu depends of Reynolds number, it is practically constant for very small hydrocyclones (Refs 9 and 10) such as the one used in this work. We felt justified, therefore, in using $Stk'_{50}.\sqrt{Eu}$ instead of a straight product of Stk.Eu as derived from first principles (see Ref. 1 or here in Chapter 3, Section 3.2). This would obviate the need to measure flowrates on the rig and, therefore, not only simplify the testing procedure but also reduce the measurement errors that propagate into the final results. As it happens, $Stk'_{50}.\sqrt{Eu}$ is the form predicted by the author of the two-phase flow theory Schubert, Ref. 11, also reported in this book in Section 3.3 of Chapter 3. The pressure drop-flowrate relationship and the flow ratio R_f, if needed, can be tested independently later.

Note that $Stk'_{50}.\sqrt{Eu}$ is independent of Q when the definitions of Eu and Stk'_{50} are substituted in from Equations 4.12, 4.13 and 4.14. Furthermore, the rig flowrates do not need to be measured for evaluation of reduced total efficiency E'_T either, because the test combination for concentration measurement is feed and overflow, c and c_o, and no flowrates are required in Equation 4.9.

The main equation relating the relevant dimensionless groups is as follows:

$$Stk'_{50}.\sqrt{Eu} = k_1.\exp(k_2 c) + k_3 \tag{4.11}$$

where the dimensionless groups are defined as follows:

The Euler number Eu is a pressure loss factor based on the static pressure drop across the cyclone:

$$Eu = \frac{2\Delta p}{\rho v^2} \tag{4.12}$$

Stk'_{50} is the Stokes number (for reduced cut size x'_{50}) defined as:

$$Stk'_{50} = \frac{x'_{50}(\rho_s - \rho)v}{18\mu D} \tag{4.13}$$

where ρ_s and ρ are densities of the solids and of the liquid respectively, μ is liquid viscosity and D is cyclone diameter, x'_{50} is the reduced cut size (see the Nomenclature for the definitions).

Both of the above equations use the superficial velocity in the cyclone body as the characteristic velocity, i.e.

$$v = \frac{4Q}{\pi D^2} \qquad (4.14)$$

The left-hand term in Equation 4.11 is a dimensionless group that has its theoretical basis in the turbulent two-phase flow theory for hydrocyclones (Ref. 11) whilst the right-hand side is a semi-empirical expression of the effect of feed concentration, which has its roots in the theory of hindered settling (Ref. 12).

The test rig described previously was run with the chalk slurry at several solids concentrations ranging up to 20% by volume, with duplicated measurements at each concentration. The range of reduced cut sizes measured was from 2 microns at low concentrations to 5 microns at 20%. The geometric standard deviation of the reduced grade efficiency curve varied between 1.8 and 2.5. The above results agree with those obtained with the conventional test methods (Refs.6, 7).

Table 4.1 shows a sample display containing data which represents one measurement point taken with the system.

Table 4.1: Example of data obtained with the computerised test method, Ref. 8.

```
------Assumptions used:----------------  ----Pressure 1 readings:-------------------
      rhos  (kg/m3): 2700
       D       (m)  : .01               Feed temp.  (deg. C): 14.5
       Sg      (-)  : 3.5               Viscosity        (P): 0.1157E-01
       xg  (microns): 3.9                             (Ns/m2): 0.1157E-02
                                        Feed pressure  (bar): 4.17
------Messages:-------------------------                 (Pa): 416616.9
  average c (%): 11.61                                  (psi): 60.4
                                        Density (g/cu.cm) do: 1.0835
  Stk'50√Eu (-): 2.2355E-03                                d: 1.1972
         Ss (-): 1.80
------Results 1:------------------------ ----Pressure 2 readings:-------------------
   rho : 999.2   ET'(%): 57.45
  c (%):11.64                           Feed temp.  (deg. C): 14.6
  x'50 : 3.007662 microns               Viscosity        (P): 0.1153E-01
   A 1 :0.274E-05   z 1 :  76.412                     (Ns/m2): 0.1153E-02
                                        Feed pressure  (bar): 3.00
------Results 2:------------------------                 (Pa): 299948.8
   rho : 999.2   ET'(%): 53.80                          (psi): 43.5
  c (%): 11.57                          Density (g/cu.cm) do: 1.0902
  x'50 : 3.41736 microns                                   d: 1.1961
   A 2 :0.273E-05   z 2 :  79.975

--------------------- (C) Fine Particle Software 1990 -------------------------
```

Figure 4.7 shows the results in dimensionless form and the best fit curve obtained by the minimum sum of squares method. This provided the constants for equation 4.11, with the following values (if c is in %):

$k_1 = 0.083419 \times 10^{-3}$,

$k_2 = 0.22359$ and

$k_3 = 1.1335 \times 10^{-3}$.

Equation 4.11 then represents the performance of the hydrocyclone within the range of operating conditions used in its testing, and can be employed, for example, as a model in particle size measurement of unknown slurries in the same rig as used in testing the hydrocyclone—see Section 4.3.3.1.

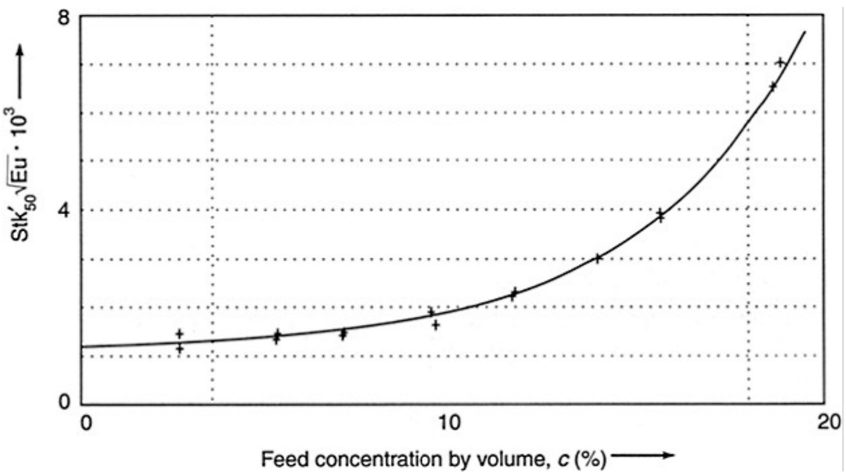

Figure 4.7: Test data obtained with a 10mm hydrocyclone

4.3.2.5 Conclusions

The advantages of the new method for testing hydrocyclones can be summarised as follows:

1. Testing of hydrocyclones is greatly simplified and sped up, compared to conventional methods, and the method can be used in research and development. The major simplification is in that it requires no flowrate measurement for Equation 4.10 and, if Equation 4.11 is used as the performance model, it does not need it either. With fewer measurements needed, reduced measurement errors get propagated into the final results. The pressure drop-flowrate relationship and the flow ratio R_f, if needed, can then be tested separately later using something as simple as the bucket-and-stopwatch method.
2. A personal computer can be used to automatically control the measurement, to take multiple readings of each variable (for improved accuracy) and to log and evaluate the data.
3. Errors of sampling, concentration measurement, flowrate measurement and particle size measurement normally present in conventional testing are either reduced or completely eliminated.
4. Any suitable feed solids material may be used for the testing but it has to be one with a mono-modal particle size distribution that approximately follows the log-normal law. This requirement is not too limiting because the test material is a matter of choice anyway.
5. The new test method and hardware has also been used by the authors in the course of the development of a new, hydrocyclone-based, on-line monitor of particle size in fine suspensions, as shown in the following Section 4.3.3.

Nomenclature

c	is concentration of solids in the feed by volume
c_o	is concentration of solids in the overflow by volume
d	is feed suspension density
d_o	is overflow suspension density
D	is the internal diameter of a hydrocyclone
E_T	is the total coarse efficiency (or recovery)
E'_T	(or ET') is the reduced total efficiency defined in Equation 4.5
Eu	is Euler number as defined in Equation 4.12
F(x)	is the cumulative percentage undersize in the feed
G(x)	is the actual grade efficiency function (curve)

G'(x)	is the reduced grade efficiency function, Equation 4.1
k_1, k_2, k_3	are constants in Equation 4.11
R_f (or Rf)	is the underflow-to-throughput ratio (by volume)
Q	is the volumetric flowrate of the feed
Stk'_{50} (or Stk'50)	is Stokes number as defined in Equation 4.13
v	is characteristic velocity as defined in Equation 4.14
x	is particle size as a variable
x_g	is the mass median of the feed solids [$F(x_g) = 0.50$]
x'_{50} (or x'50)	is a the reduced cut size [$G'(x'_{50}) = 0.50$]
Δp	is static pressure drop across the hydrocyclone
μ	is liquid viscosity
ρ (or rho)	is liquid density
ρ_s (or rhos)	is solids density
σ_g (or Sg)	is the geometric standard deviation of F(x)
σ_s (or Ss)	is the geometric standard deviation of G'(x)

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