Scaling up filtering centrifuges.

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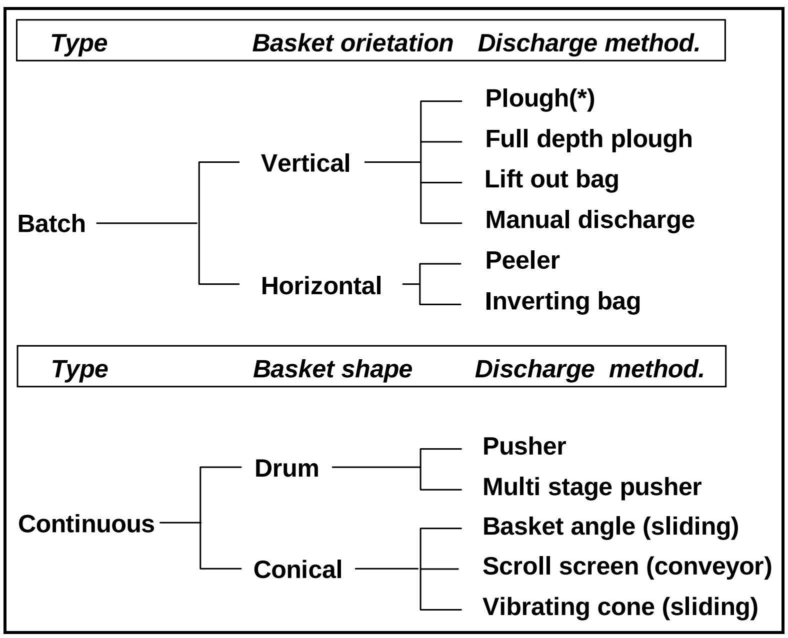
Abstract.
The scale-up of filtering centrifuges from laboratory or pilot scale tests to full plant scale is discussed. Several aspects of full scale centrifuges and small scale testing are considered including the test sample size, collection method and physical characteristics of the sample. The information provided is intended to assist the potential filtering centrifuge user and provide an understanding of the scale-up process, it's limitations and interdependencies.

Introduction to filtering centrifuge.
There are a wide variety of filtering centrifuges and each type is produced to satisfy one or more requirement of the solid-liquid separation market. The various types are categorized in the table below firstly in terms of : batch or continuous operation, secondly : orientation of the basket (vertical or horizontal) and finally : the method of discharge of the filter cake from the basket. This simple classification goes some way to show the range of filtering centrifuges available - for more details see reference 1.

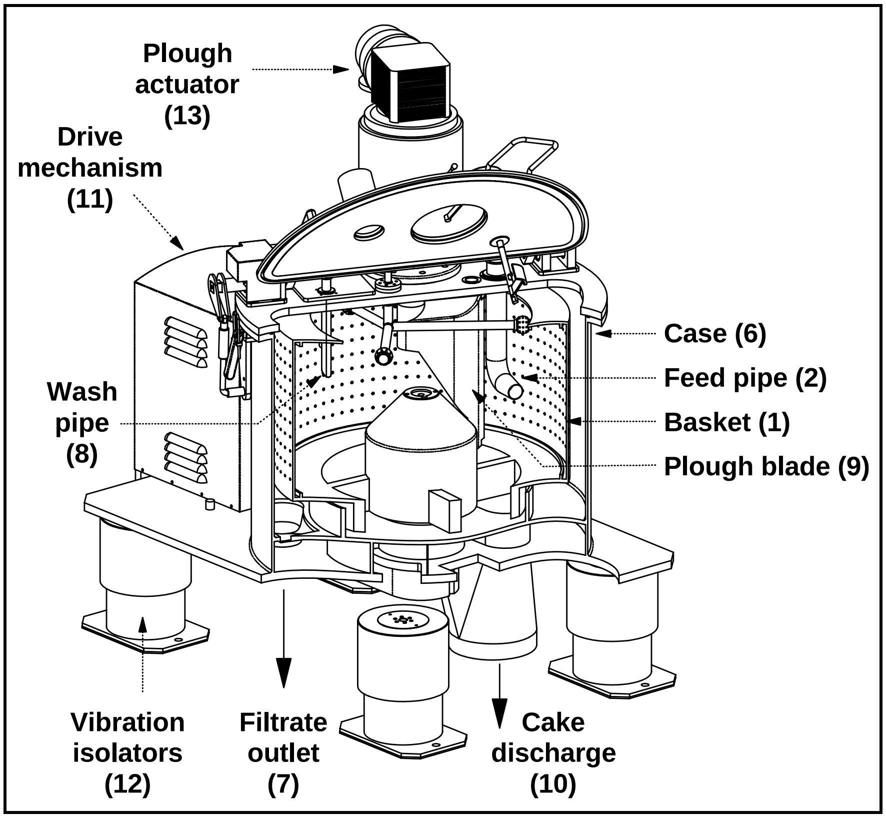
Table 1. Simple classification of filtering centrifuges.



Discussion in this paper is limited to the standard type of filtering centrifuge. This is marked (*) in Table 1 and is characterised as a batch, vertical, plough discharge filtering centrifuge. Figure 1 shows a schematic of such a centrifuge and figure 2 shows the main components on the basket where the filtration process takes place. See references 1 & 6 for an introduction to the selection of a centrifuge type for a particular duty.

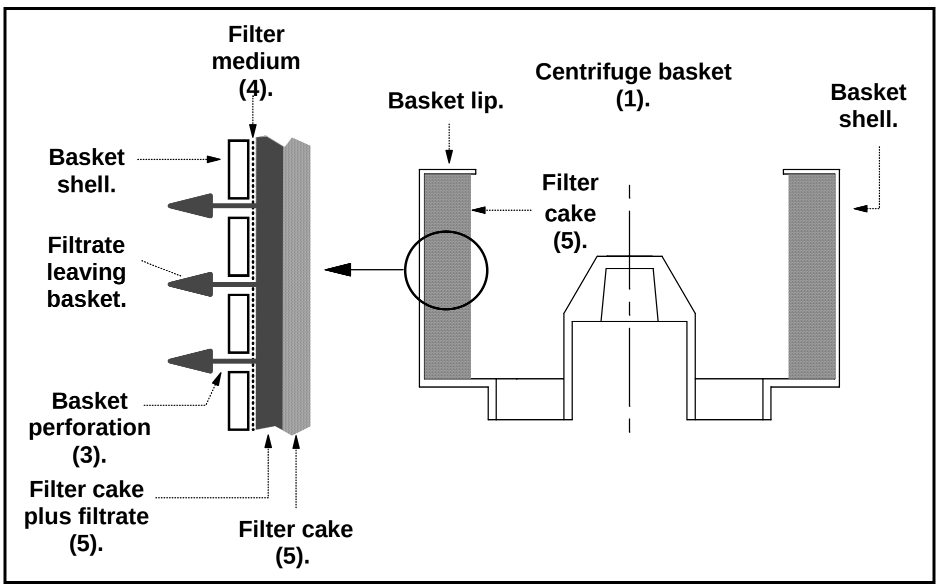
The centrifuge basket or drum (1) contains many perforations to allow the passage of liquid during the filtration process. The basket supports the screen onto which the material to be separated is placed by the feed pipe (2). Figure 2 is a cross section of a basket showing the perforations (3), screen (4) and solid - liquid suspension in the process of being separated. The cake (5) forms an annulus around the wall of the basket, with a thickness typically 10% of the basket diameter. The basket rotates at a rate sufficient to generate an angular acceleration (often termed 'G') which drives filtration in the same way the differential pressure drives the filtration in a pressure filter.

Figure 1. Schematic of typical batch filtering centrifuge.



Courtesy of Broadbent Centrifuges.

Figure 2. Section of a batch centrifuge basket.



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A typical process cycle for a batch filtering centrifuge comprises the following 7 steps :

1) ***Accelerate to feed speed.*** The basket (1) is accelerated to a speed suitable for feeding.
2) ***Feeding.*** The feed solid - liquid suspension is added to the basket via feed pipe (2).
3) ***Accelerate to spin speed.*** Accelerate the basket to a high rpm to produce a high 'G' to drive the filtration process.
4) ***Washing.*** If required the filter cake is washed via wash pipe (8).
5) ***Drying.*** Continue spinning at high 'G' to dry the filter cake. The filtrate leaves via outlet (7).
6) ***Deceleration.*** Slow the basket to a speed suitable for cake discharge.
7) ***Discharge.*** Discharge the cake through the bottom of the basket (10) using the plough mechanism (9 & 13).

Typical process cycle times range from 150 to over 10,000 seconds depending on the process. Scale-up test-work is usually associated with parts (2), (4), (5) and (7) with most attention usually being directed towards (2) and (5).

Fundamentals of filtering centrifuges.

A basic knowledge of the physical processes that occur during centrifugal filtration aids the understanding of scale-up from laboratory or pilot plant tests to full plant scale. This section attempts to provide a rudimentary introduction.

Filtration starts as soon as the feed mixture of particles (solids) and liquid enters the rotating basket. As filtration proceeds the particles are pressed together by the centrifugal forces and the liquor flows through the gaps between particles and then through the holes in the filter screen or cloth and out of the basket thereby effecting the separation - see figure 2.

The process of filter cake formation and removal of the liquor from the cake occurs in several phases. The simplest description involves three phases :

Phase I occurs when all the particles have settled to the basket wall producing a filter cake and they are still fully immersed in the liquor which is draining through the gaps between particles. This continues until the liquor level drops to the level of the particles whereupon the second phase commences.

Phase II is taken as that period when the liquor recedes through the filter cake and gaps between the particles are no longer all filled with mother liquor. The exposed particles are covered in a thin layer of liquor which drains slowly through the cake - the drainage of this thin film is **Phase III** of the filtration.

Phase I proceeds rapidly and is replaced by phase II. Phase II and III start at virtually the same time; however Phase II predominates until close to the end of filtration. Finally when Phase II is complete all that remains is Phase III, plus non filtration effects such as air drying. Ignoring non filtration effects phase III fixes the final cake dryness. A more complete description would include an additional cake formation phase. See references 1,2 & 3 for more details of filtering centrifuges and filtration in general.

For most users of filtration centrifuges it is the performance in phases II (initial purging of the liquor) and phase III (progress towards final cake dryness) that are most relevant. A simple analysis allows the basic dependencies of phases II and III filtration rates to be derived in terms of the physical characteristics of the feed material (see reference 1). The results of this simple analysis, whilst far from rigorous, do provide a basic understanding of the main physical mechanisms involved and allow the centrifuge user to understand the effects of various physical characteristics of phase II and phase III filtration.

Phase II filtration (liquor level within filter cake measured from the cake surface) is proportional to :

$$\frac{(\text{Average particle size})^2 * (\text{Centrifuge G}) * (\text{Spin time})}{(\text{Liquor viscosity}) * (\text{Filter cake thickness})}$$

Eqn 1.

Equation 1 ignores potentially important factors such as the spread of particle size either side of the average, particle shape and the compressibility of the cake formed within the centrifuge.

The end point of Phase III filtration (ultimate final dryness after a long spin time) is proportional to :

$$\frac{(\text{Liquor surface tension})}{(\text{Centrifuge G}) * (\text{Average particle size})^2}$$

Eqn 2.

Equations 1 & 2 are useful in providing a rudimentary guide on how the physical properties of the feed material and basic physical aspects of the centrifuge affect the separation performance. The centrifugal force ‘G’ and average particle size both appear in equation 1 and 2 whereas other aspects such as cake thickness and spin time appear only in equation 1 and consequently have a lesser affect on overall separation performance. Whilst spin time and cake thickness undoubtedly affect separation performance the stronger dependence on ‘G’ and particularly particle size suggested by equations 1 & 2 is found in practice.

Physical limitations of filtering centrifuges.

When discussing scale-up it is worth mentioning the main factors which limit the size of filtering centrifuges. At the small end of the scale these are practical considerations such as physical access to the basket and the economic cost per unit of throughput. For centrifuges with automatic feeding, washing and cake discharge there is a minimum basket diameter below which there is insufficient room to fit the services and mechanisms required. Typically this basket diameter is around 800mm, which with a maximum allowable cake depth of perhaps 100mm gives an opening in the top of the basket of 600mm. Smaller manual or semi automatic centrifuges are available although these are not common in modern process plants.

The majority of small centrifuges are generally designed for laboratory or pilot scale use. Figure 3 shows two fume tight laboratory scale test centrifuges together with 260 and 100 mm diameter baskets. The dual basket option allows testing on a wider range of sample sizes.

Figure 3. Laboratory scale centrifuges with 260 & 100mm basket options.

Courtesy of Broadbent Centrifuges.

At the opposite end of the scale the largest centrifuges are limited in basket diameter by the materials of construction. The basket material must be strong enough to support itself when spinning empty with any remaining material strength (after due allowance for safety factors etc) being used to support the filter cake and liquor in the basket. The significant point is that the proportion of the basket material strength required to support it's own weight increases with basket diameter *(i.e. for a given 'G' the self stress is proportional to diameter* ^{2}*)*. This means that as the basket diameter increases a smaller proportion is available to support the filter cake etc. For basket materials currently available this places a limit on the maximum basket size. For a basket capable of running at a separating force in the range 500-1000G the practical limit is around 2000-2200mm diameter. Similar considerations apply to all centrifuges regardless of type and these basket material limitations explain why the maximum 'G' available from centrifuges drops as the basket diameter increases.

The basket volume depends not only on diameter but also on the depth and thickness of filter cake. It is normal practice to have a basket depth around 50-70% of the basket diameter. Depths greater than this make distributing the feed within the basket more difficult and often lead to stability and vibration problems when spinning. Cake thickness is generally governed by the filtration rate through the cake (see eqn 1). A typical maximum value for a freely filtering crystalline material is 250mm. In practice therefore the upper limit for a filtering centrifuge size is a diameter of 2000mm with a depth of 1200mm and a cake thickness of 250mm giving an overall volume 1.65M^3 and a filtering area of 7.8M^2. Such a design would only find practical use for freely filtering materials. The limitations outlined above should be borne in mind when scaling up from laboratory or pilot plant tests.

Scale-up from test samples.
There are many aspects to consider when selecting a full plant scale filtering centrifuges based on smaller scale trials. Those discussed here are :

1) Particle size and shape distribution of feed material.
2) Collecting the test sample of feed material.
3) Small scale centrifuge testing.

For a more complete discussion see references 1, 3, 4 & 5.

The discussion that follows assumes :

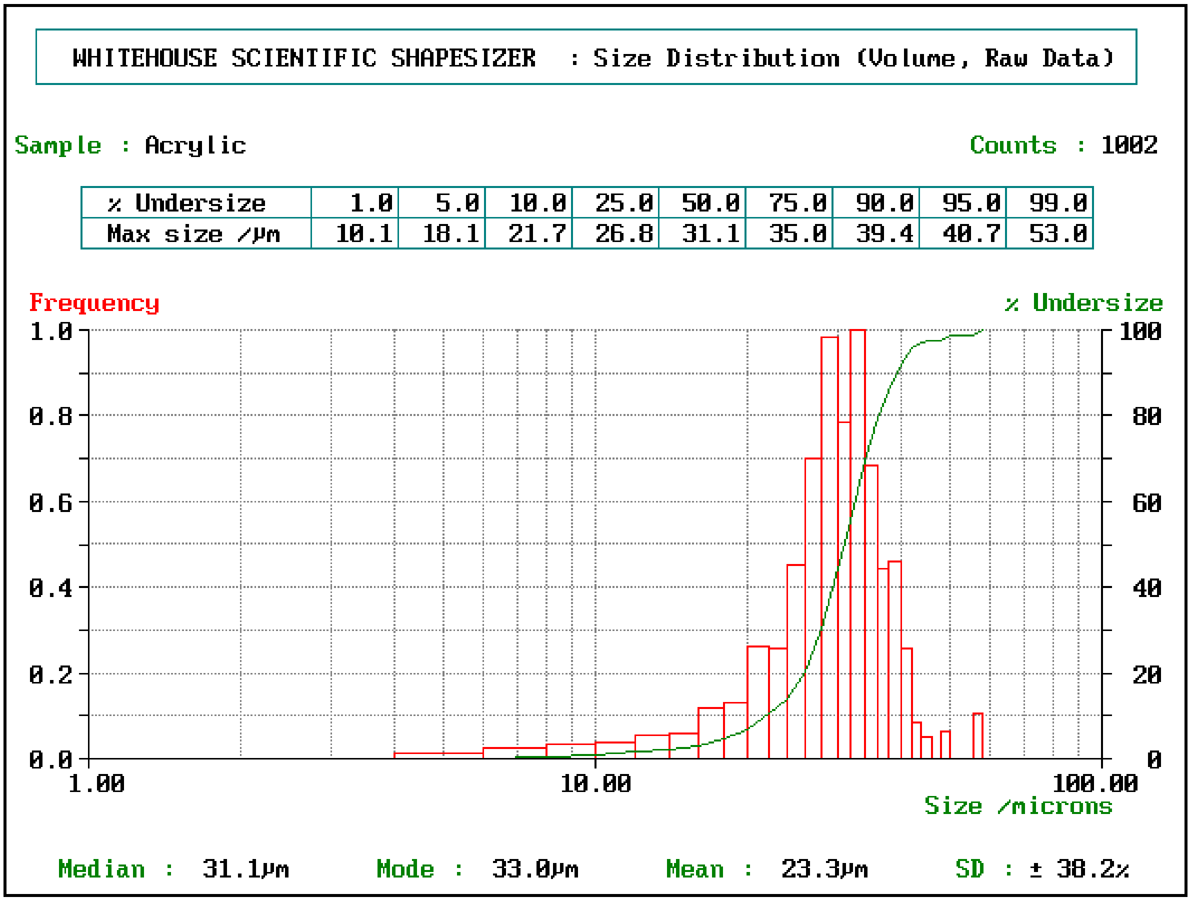
- There is no full scale test data available - if there is then use it.
- Samples are taken from a small pilot plant.
- The solids phase is heavier than the liquid phase (note that if the solids are lighter than the liquids filtration still occurs but the details of the scale are different).
- Non filtration drying effects are ignored (e.g. air drying during spinning, additional heating).
- The centrifuge under investigation is a automatic vertical axis batch filtering centrifuge (see (*) in table 1 and figure 1).

Particle size & shape.
Most centrifuge users primary interest is the mass of ‘on-spec’ product discharged by the centrifuge. The centrifuge operates by aiding the removal of liquor from the surface area of the particles in the feed. The link between the mass of the particles and their surface area is the particle size and shape distribution and therefore this plays a central role in defining the centrifuge performance. It will be no surprise that the particle size distribution - and things that can change it - are most important when predicting or scaling up centrifuge performance.

The particle size is often given as a single figure or range such as a D_{50} of 80-100 microns and whilst this is useful information it is not the complete picture. The ideal is a particle size distribution which shows the proportion of particles present in the sample as a function of size. Figure 4 shows such a distribution. In this example the D_{50} is 31.1 microns and 10% w/w of the sample has a particle size of 21.7 microns or less. This additional information is important as it has a large effect on the overall surface area of the sample and therefore a large effect on the separation performance of any centrifuge. In the example of Figure 4 20% of the surface area comes from the smallest 8% of the solids and any increase in the proportion of fine particles will have a marked effect on the surface area of the sample and therefore separation performance.

In addition to the size distribution the shape of the particles is also important. Needle shaped particles are more difficult to discharge from a centrifuge and often prone to breakage during pumping, feeding or discharging. Generally a particle shape close to 1:1 aspect ratio is the easiest to process in a centrifuge.

Figure 4. A typical particle size distribution.



Courtesy of Broadbent Centrifuges.

The test sample.

The test sample must be representative of the final centrifuge feed. The ideal situation occurs when a full scale plant already exists, good sampling techniques are followed (see reference 7) and the feed material is stable over time. Unfortunately this utopian situation is rare. It is more common for the sample to come from a pilot scale plant where the feed material is limited and is produced using equipment different in type as well as scale from that envisaged in a full scale plant. In this case the accuracy of any tests or associated scale-up may suffer significantly. Some of the practical issues relating to test samples are :

Time delays
If centrifuge testing is not conducted on the pilot plant site then there may be a significant time delay from collection of the sample to testing in a small scale centrifuge. For samples that may decompose, recrystallize, agglomerate or otherwise change their physical characteristics over time then every effort needs to be made to reduce delays in the testing process. Other options include adding inhibitors to reduce biological or chemical changes, planning to avoid delays, or providing the sample as a dry solid and a separate liquor sample to be reconstituted prior to the small scale centrifuge testing. This latter approach brings it's own set of problems - see below.

Sampling techniques.
A lot has been written about sampling techniques - see reference 7 for a general background. A non representative sample for whatever reason will invalidate any test. It is advisable to take several samples and compare them in terms of particle size distribution and solids concentration etc to gauge the sampling error. Ideally these samples should be taken from two or more points to highlight any systematic errors introduced by sampling. It is particularly important to ensure that the sample point doesn't preferentially collect one size of particles over another. Examples of this are a sampling at the bend of a pipe where large particles predominate at the outside radius of the bend due to centrifugal effects. Another example is sampling from a corner of an agitated tank which are often 'dead zones' where there is little agitation. This leads to samples with a reduced solids concentration and a preponderance of fine particles.

Design of pilot plant.
Samples produced by a prototype small scale pilot plant are often significantly different from those produced by a full scale industrial plant. These differences generally manifest themselves in terms of particle size distribution and solids concentration - both of which can have a profound effect on scale-up. Where these effects are likely to occur it is prudent to perform a sensitivity analysis on the effects of solids concentration and, most importantly, particle size distribution.

Reconstituted test samples.
Transport delays or pilot plant layouts often dictates that liquor samples (taken from another separation step) and solids samples (often ex dryer) are provided separately. It is then the task of the test lab to mix the solids and liquids in the correct proportions to produce a reconstituted sample. Wherever possible it is important to check that the reconstituted feed is adequately representative of the original.

Solids taken from a dryer are often changed by the passage through the dryer and any associated conveyors. Thermal drying can produce agglomeration of particles or change to the surface characteristics of the solids making them extremely difficult to wet-out without the addition of surfactants. In all these cases the net effect is one of significantly altering the effective particle size distribution.

Small scale centrifuge testing.
Performing the small scale tests is part science, part comparison with earlier full scale applications where the results are known and part black art. Extensive testing and theoretical modelling will reduce the level of black art and increase the science and give the best results. In

practice most scale-up investigations are satisfactorily handled by centrifuge vendors or chemical company in-house laboratories on a short timescale at reasonable cost. This section considers some of the important tests undertaken in a scale-up investigation. See reference 1 for a more extensive discussion.

Cake bulk density measurements.

The density of a compacted filter cake in a centrifuge is more than the loose packed density of dry particles and less than the theoretical solid particle density. Accurate measurement of the density of dried cake within the centrifuge basket is necessary to be able to select a suitable full scale basket volume for the particular application. Measurements are usually performed using a small scale laboratory centrifuge where the weight of the entire basket with and without the cake can be used to calculate the density.

Filtration rate measurements.

Measurement of the filtration rate through the cake per unit area of screen provides information for scale-up of the feed and drying phases of the centrifuge cycle. Correct feeding of a batch centrifuge requires that the rate of addition of the feed liquor is approximately balanced by the feed liquor filtration rate through the cake at the centrifugal ‘G’ used for feeding. If the rate of liquor addition is lower than the filtration rate then the feed does not distribute evenly in the basket and the full capacity of the centrifuge is not realised. If the liquor is added too fast then the basket is being ‘overfed’ and surface liquor will collect above the cake. This may be acceptable to a limited degree but is liable to cause high levels of vibration during feeding in certain circumstances. A good feed rate for scale-up purposes is one where the liquor addition rate matches the filtration rate. Tests are conducted at various basket speeds to measure the filtration rate and to ensure that the material is distributed evenly within the basket during feeding.

Once the filtration rate per unit area of screen is known, scale-up to a full sized basket is made by adjusting the feed rate for the larger screen area and thicker cake of the full scale centrifuge.

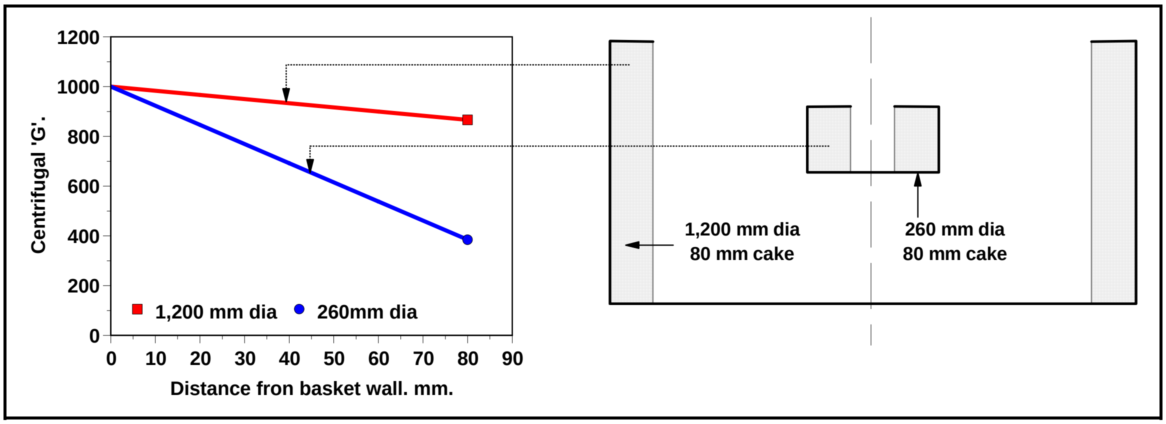
Filtration rate measurements can be made in several ways. One method that provides extensive information requires the segregation of the solids and liquid in the feed. Initially a normal feed (solids & liquid) is used to form a uniform cake of known thickness in the test centrifuge basket. The feed liquor is then added onto the cake in increasing quantities until free liquor appears on the surface of the cake. The liquor flow rate that maintains this condition is the filtration rate at that particular ‘G’. Enhancements to this approach include placing the centrifuge on load cells to continuously monitor the mass in the basket. Monitoring the reducing weight of the basket after the liquor feed has been turned off gives the drying rate of the cake during spinning.

Cake compressibility and cake thickness.

Materials are often classified as compressible or incompressible whereas in practice all cakes are compressible to some degree. The centrifugal pressure on the particles in the cake forces them closer together reducing the cross sectional area of the pathways for the liquor through the cake and therefore reducing the filtration rate. Equation 1 suggests that filtration rate will increase linearly with ‘G’ for a given cake thickness; however if the cake is compressible the increase will be less than this. Measurement of the filtration rate at two or three ‘G’ levels will provide a clear indication of the degree to which the cake is compressible.

Centrifuge testing automatically includes the complex effects of cake compressibility in the results. However if only small scale tests are possible then the effects of the thicker cakes on a full scale centrifuge must be included as a scale-up factor. To aid scale up to larger lips, laboratory centrifuges can be provided with baskets that have an oversized lip, however the scale up is not exact as the ‘G’ at the surface of an 80mm cake in a 260mm diameter basket is just 38% of the ‘G’ at the basket wall whereas the same cake thickness in a 1,200mm diameter basket the figure is 87%. Figure 5 shows this effect graphically. Nonetheless the use of a deeper lip in a small test centrifuge is a useful tool which reduces the need for scale-up based on cake thickness.

Figure 5.
Variation of ‘G’ with cake thickness for 1,200 and 260mm diameter baskets.



An alternative approach relies on experience of other separation duties where the full scale process results from cakes with similar compressibilities and particle size distributions are known. Generally cake moistures tabulated against spin time follow similar patterns and information from other separation applications is an invaluable tool when attempting to scale-up on a new application.

One simple rule used in some circumstances is to scale the time required to reach an intermediate cake dryness (eg end of phase II of filtration) as the square root of the cake thickness (reference 8). This is a rough guideline at best and it is important to note that the limiting dryness (after a long spin time) is dependent on centrifuge G, surface tension and particle size and is largely independent of cake thickness - see equation 2. However the thicker the cake the longer it takes to reach this limiting dryness.

Cake discharge tests.

The mechanical discharge of the dried filter cake from a centrifuge is commonly referred to as ploughing or scraping. Testing the ploughing characteristics of the dried cake material is important and test centrifuges fitted with small scale ploughs are available for this purpose. In addition to assessing how the cake discharges from the centrifuge the ploughing test will leave a residual bed in the test centrifuge basket. This is a small layer of cake (typically 2-6mm thick) that has not been removed and unless special actions are taken to remove it before the next batch of feed is processed it will remain in the basket. This residual bed may reduce the cake filtration rate and in extreme cases could become virtually impervious to the filtrate bringing filtration to a halt. In such cases the residual bed must be removed before a further batch of feed can be processed.

Repeating the small scale test using a basket with the residual bed in place from earlier test(s) allows these effects to be measured and minimized by the use of filter aid etc. The results will indicate the number of batches that can be processed before the residual bed must be cleaned out of the centrifuge.

Summary.

The main issues to be considered as part of any scale-up are :-

- Use large samples.
- Take great care to obtain representative samples - particularly with regard to the particle size distribution.
- Perform the test as soon after sampling as practical.
- Use the largest test centrifuge possible in the circumstances.
- Perform tests to investigate feeding, washing, drying, ploughing and the effects of residual bed blinding.
- Do not reuse feed material many times as breakage during feeding and ploughing will change the particle size distribution.

Testing can be time consuming for all parties involved, however time spent on a representative test that investigates the sensitivity of the results to any known areas of uncertainty is generally well worth it. The costs to the end user and the centrifuge supplier of getting it wrong in a full scale plant are almost always higher.

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