

## "Separation, thickening, classification and washing of wheat starch with hydrocyclones"

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The paper reviews the ways of boosting the performance of hydrocyclones by using series connections and recycles, with particular reference to wheat starch. Different applications, alternative arrangements and applicable design rules are discussed, with quotes of specific case studies encountered in industry. Aimed at practitioners such as chemists, process engineers or plant operators, as well as students and academics.

### Introduction

Hydrocyclones are now well established in the starch industry as separators of choice when it comes to washing, thickening or classification by particle size (fractionation), shape or density. When dealing with the finer starches such as wheat starch, hydrocyclone performance is pushed to its limits and every 'trick of the trade' has to be used to achieve it. Although this is a technical paper describing the design and operating rules, installed processes and series arrangements, greater detail and the actual design equations can be found elsewhere<sup>1</sup> and in chapters 6, 15 and 16 in ref<sup>2</sup>. All of the technology described here is of course applicable to any other starches that also contain fine fractions but the author's experience is almost exclusively limited to wheat starch.

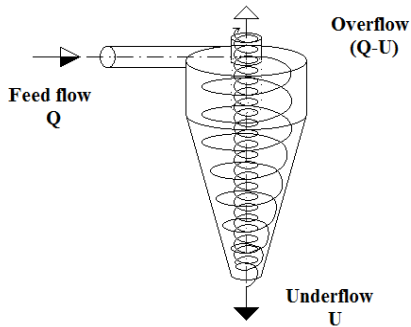


Fig 1. Schematic diagram of a hydrocyclone and of the vortex inside it. Flow rates  $Q$ ,  $U$  and  $Q-U$  represent total volumetric flows in the three streams shown.

Fig 1 shows of a hydrocyclone in a simplified schematic diagram. In processing of wheat starch, for its low density and small particle size, the hydrocyclones have to be small in internal diameter (usually 10mm) and of the narrow cone angle design as depicted. Due to the small size and the correspondingly low flow capacity of such a small unit, many have to be installed in parallel (usually in boxes) to give the required flow.

It is easy to see the advantages of a hydrocyclone as a separator as it is essentially a piece of pipe with a tangential inlet, a cone at the bottom and a lid on top, with the overflow pipe (vortex finder) protruding through it. This simple piece of plumbing has no moving parts and can be installed easily and cheaply. The tangential inlet generates a standing vortex in the flow inside and it causes the separation of particles from the flow by centrifugal force. There has to be a density difference between the particles and the liquid for the separation to take place so the separation is essentially by density and particle size. In addition to that, due to the steep gradients in the flow, the separation can also be by particle shape because of differences in orientation of the settling particles. All of that is very useful in starch applications but one general problem is that a hydrocyclone on its own, in a one-stage operation, has some limitations in performance which for fine starch particles and their relatively low density need extending.

If the particulate system presented to the hydrocyclone is of uniform density and of uniform, granular particle shape, the separation is by particle size as shown in Fig 2. The curve is called grade efficiency curve and, like a 'transfer' curve, it shows how much of the different particle sizes in the feed is separated into the coarse product leaving through the underflow. If one needs to work out how much mass in total will be removed as coarse product, it is an integral of the product of feed size distribution by mass (or volume) and the applicable grade efficiency curve of the hydrocyclone. Similarly, we can also predict the particle size distributions in the two outgoing streams if needed.

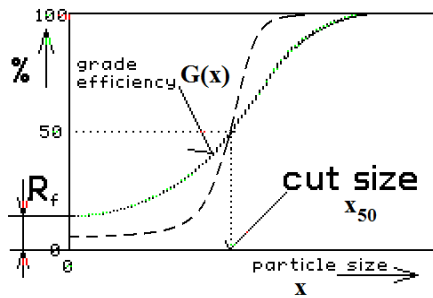


Fig 2. Typical shape of the grade efficiency curve  $G(x)$  of a hydrocyclone (**dotted curve**), the definition of the cut size  $x_{50}$  and the effect of the splitting of the flow  $R_f$ . The **dashed curve** is much steeper (giving a sharper cut), with reduced intercept, as can be obtained with a multistage arrangement. Please note that this may also move the system cut size to the right or left (not shift is indicated in Fig 2) depending on the arrangement used.

Coming back to the grade efficiency curve itself, it can apply to a single hydrocyclone stage or a whole multistage system with or without recycles. Its most important feature is its position along the x-axis. The commonest way of describing this position is the size at which the grade efficiency reaches 50%, and we engineers call it 'cut' size  $x_{50}$ .

There are two other important properties of the curve: the sharpness of cut and the split ratio. The steepness of the curve, as described by many different indices, is a measure of the sharpness of cut i.e. how clean is the separation between two different fractions in the two outgoing streams in particle size (if the grade efficiency is plotted against particle size), in particle density or particle shape, if plotted against those properties respectively. In wheat starch processing, all of this is highly relevant as we may need to separate size fractions in some processes and in others different particle densities or particle shapes (gluten from starch, for example). As can be seen in Fig 2, the sharpness of cut of a single hydrocyclone is not particularly good but a multi-stage system can improve this remarkably as shown by the dashed curve.

The last characteristic parameter is the split ratio  $R_f$  which gives rise to, and is usually equal to, the intercept on the y-axis in Fig 2. Using the notation from Fig 1, it is defined as the ratio of the total underflow volumetric rate  $U$  and the total feed flow rate  $Q$ , i.e.

$$R_f = U/Q$$

This is because the underflow is in the form of a slurry, and the liquid content and to some extent also the particles in it, carry some of the finest fractions in the feed into the underflow. The result is that the grade efficiency shows a finite efficiency for particles approaching zero in size (the intercept in Fig 2), which the centrifugal action within the hydrocyclone has no chance of recovering into the underflow. This effect of the splitting of the feed flow into the two outgoing streams affects all fractions present, of course, but for the finest ones it is most visible. When the purpose is to maximize recovery of all solids, the effect is welcome and can be boosted by simply taking more liquid with the solids by increasing the size of the underflow orifice (though one would not necessarily want to do that as it dilutes the underflow). When the purpose is classification (or starch washing) to produce a **coarse product free of fine particles** (or granular starch particles free of the hydro-dynamically lighter gluten), the effect is detrimental and the split ratio has to be minimized.

In a single hydrocyclone,  $R_f$  can be reduced by reducing the size of the underflow orifice but this coarsens the cut which usually is not an option with wheat starch. Reduced split ratio can, however, be once again achieved by using a multi-stage system as indicated in Fig 2 by the dashed curve. Finally, when the purpose is classification to produce a **clean fine product** free of the coarse particles, the splitting of the flow does not affect the quality of the fine product, it just reduces the yield of it.

Let us now have a look at what needs to be achieved in wheat starch processing and how that translates into the use of hydrocyclones. As a natural product, wheat starch has no standard particle size distribution but it usually looks like shown in Fig 3. It is bimodal (having two peaks), therefore consisting of two distinct fractions or species. Particle density is around 1500kg/m<sup>3</sup>. If one needs to recover as much as possible of all sizes of starch present, the cut size of the hydrocyclone (if just one stage is used) or of the separation plant (for multistage arrangements) has to be as low as possible, preferably below the minimum particle size present. Unfortunately, due to the low density difference between the wheat starch particles and water (about 500 kg/m<sup>3</sup>), a single 10mm hydrocyclone operated at the maximum

practicable pressure drop of 6 bar is unlikely to give a cut size lower than about 6 microns. This is not low enough as there are particles present in the starch that are finer (down to about 3 microns) and one would thus be losing some fine starch to the overflow. One can remedy that, however, by reducing the effective cut size by using a series in the direction of overflow, as further discussed later.

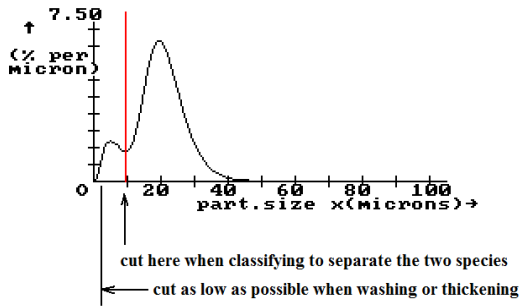


Fig 3. A typical bi-modal distribution of particle size of wheat starch (by mass or volume) showing where we need the cut size to be when classifying or washing/thickening.

As can be seen from Fig 3, if the two separate fractions present in wheat starch are to be separated, the approximate cut size of 10 microns is needed and that is achievable without the need for lowering the cut size in a series on overflow. In all other cases we have to combine overflow and underflow series in one installation, as shown later.

#### Series connections in the direction of overflow

These connections are used either to lower the cut size or to re-classify the fine product (by a process sometimes called refining). In its simplest form it is connecting hydrocyclones one after another to repeat the separation on the overflow of the previous stage as shown on the extreme right of Fig 4 for a three-stage installation. Besides the simple overflow series it also shows the use of re-cycling arrangements A and B which are used to compensate the otherwise high overall  $R_f$  ratio in this arrangement. These arrangements also give the designer the option to set up the first stage as a thickener (operated with high underflow concentration) and following stages as clarifiers (operated with dilute underflows and higher cut sizes as a result).

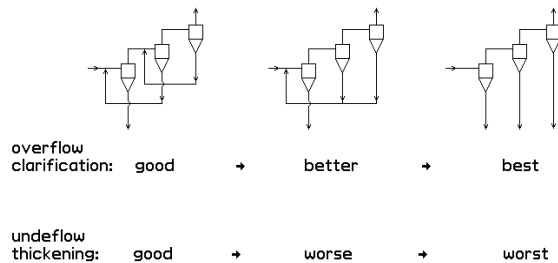


Fig 4. Three alternatives of a **three-stage overflow series**: comparison of the two underflow recycling arrangements A & B with a simple overflow series. Normally, there will be pumps in between the stages (not shown in the picture) but the simple overflow series on the right has been known in some cases to be driven by a single pump at the front. However, in that case the effect of the extra back pressure on the overflow of the initial stages has to be offset by suitable adjustment of the underflow orifices in those stages.

In classification of wheat starch, the overflow series has been used to produce a clean fine component of the bi-modal starch, free of the coarse fraction. Fontein<sup>3</sup> first patented this series for such a purpose with the view of producing fine starch which he identified as more valuable. However, for the case of producing a clean coarse product this would be no good as it would be polluting it with fines due to the relatively large overall split ratio in this arrangement. For this, the underflow series is a better option as shown later.

In washing of wheat starch, the overflow series plays a very important part and it is now quite routinely used to treat the system overflow from a counter-current washing train, as will be shown later in this paper (Fig 6). Without it (or another more efficient separator like a sedimenting centrifuge as often used in USA), counter current washing trains that use hydrocyclones would otherwise lead to unacceptable losses of starch to system overflow (where only gluten is wanted). When given the alternatives presented in Fig 4, designers sometimes opt for recycling arrangements A or B in

trying to reduce the amount of water returning to the washing train. However, it is often possible and better to use the most efficient arrangement of the simple overflow series without recycles but compensate for the increased water return by adding less water elsewhere, such as at the front of the washing train. I have advised a British wheat starch producer along these lines and this lead to significant increases in starch recovery.

### Series connection in the direction of underflow

In spite of several options in this category being available to industry in general (see Chapter 6 in Ref<sup>2</sup>), there is really only one option useful for wheat starch. This is because the simple underflow series (connecting hydrocyclones one after another to repeat the separation on the underflow of the previous stage) always leads to a coarsening of the system cut size. In case of wheat starch, one therefore always has to compensate by using overflow recycles and, therefore, these are always present. The available system is shown schematically in Fig 5, as an example for a three-stage arrangement.

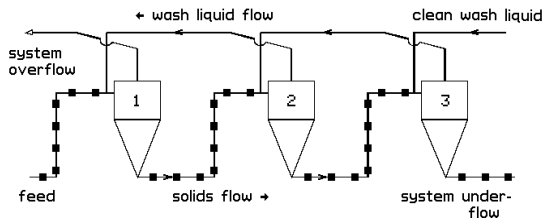


Fig 5. A schematic diagram of a three-stage underflow series with recycles as used for classification, washing or thickening. Here recycles must be used because a simple underflow series would otherwise coarsen the cut too much and also require much larger amounts of wash or dilution liquid. In washing, this system is for obvious reasons called 'counter-current washing train' and it may use up to 20 stages. Once again, pumps (not shown in the picture) have to be installed in between stages.

This may be used for thickening, washing or classification. The streams depicted with large square dots carry the solid starch particles from left to right, being washed or classified by a stream of wash/dilution liquid passing through in the opposite direction from right to left. In each hydrocyclone stage the solids stream is first diluted by a returning, cleaner stream, then thickened in a hydrocyclone that sends the decanted liquid backward to the previous stage and the thickened solids forward to the next stage.

One significant application of this arrangement in classification is that of producing coarse starch as stiling material for manufacture of carbonless copy paper. The technology was first developed to use arrowroot starch which is suitably coarse and mono-modal but, as the supply of arrowroot worldwide is too limited, the coarse component of wheat starch was found as a good substitute. The fine component has to be removed really well as it would lead to smudging when using the copy paper. There are problems when attempting to classify wheat starch dry, by air classification, because fine powders like starch are difficult to disperse well in air and to keep it dispersed during the classification process. As most processing of wheat starch, including washing, is done in water and as dispersion of starch particles is much easier in water, classification can be done wet, in a system like in Fig 5. Bond<sup>4</sup> patented a wet hydrocyclone process for this specific application and this has been used widely since, in preference to air classification. The purpose of the arrangement in Fig 5 in wheat starch processing can be identified easily: when it is used with only 2 or 3 stages and without an additional separator on its overflow (as depicted), it is clearly a classifier. In washing, it would not be very efficient and it would be losing significant amounts of the fine starch into the gluten stream. During the lifetime of Bond's patent, there have been attempts to use the arrangement in Fig 5 for classification, under the guise of counter-current washing. Yet, for outside pretences, a completely redundant air classification step was run just to avoid patent litigation.

By far the greatest use of the underflow series with recycles in Fig 5 is in counter-current washing. In washing of wheat starch, this is the removal of a soft, semi-solid and light material (the soluble and insoluble proteins i.e. gluten) from granular solids (starch particles). Hydrocyclones are ideal separators for this application because of the high shear forces in the flow which separate the semi-solid, sticky gluten from the granules of the starch particles. Gluten as a product is concentrated into the system overflow which is then further dewatered in subsequent processing whilst the washed starch particles are concentrated into the system underflow, again possibly further dewatered/dried.

As was pointed out previously when discussing the selection of the operating cut size in washing and/or thickening of wheat starch, the cut size of hydrocyclones on their own cannot be depressed low enough to prevent the very fine fractions of starch escaping into the overflow. So in a series connection on underflow which coarsens the cut

size anyway, an additional separator (or hydrocyclone overflow series) has to be bolted onto the washing train. Fig 6 gives a typical wheat starch washing system (9-stage as an example) which normally has to employ such an additional separator (or a series) on the system overflow. Its function is to return the finest starch fractions which the first washing stage is not capable of separating efficiently. A sedimenting centrifuge (Merco by Dorr-Oliver, for example) is sometimes used in this role in US but a three-stage overflow series of small diameter hydrocyclones tends to be used in UK and elsewhere in Europe. Fig 4 gives the three-stage installation alternatives and their merits, as encountered in consulting practice.

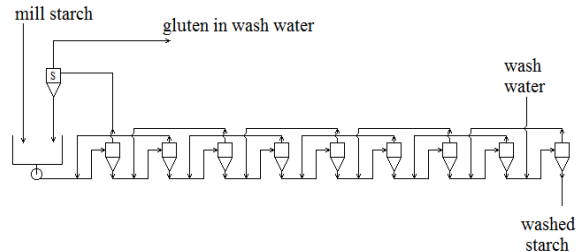


Fig 6 A line diagram of a typical starch washing plant. S is the additional separator or overflow series usually employed to reduce starch losses to overflow.

A well-designed arrangement with the recycles usually plumbed-in (i.e. no intermediate sumps but a pump before each hydrocyclone stage) is capable of excellent washing efficiency coupled with minimum solids losses to overflow and good thickening to 23 to 24 Baumé (this is a slurry density measurement using hydrometers; 24 Baumé corresponds to about 40% by volume for starch). The static pressures around the system allow a fully enclosed, 'plumbed-in' arrangement but one problem is that samples cannot be easily accessed (as would be if intermediate sumps were used) and the resulting lack of knowledge of the solids concentrations around the system may lead to incorrect and wasteful remedial work. One consulting visit to a wheat processing plant in Ireland where the washing train set up by the manufacturer failed to produce the thickening performance expected and only 17 Baumé was achieved no matter how much the wash liquid supply was reduced. As a desperate remedy, the user installed an additional three-stage hydrocyclone thickening series on the system underflow that then produced the desired underflow density of 24 Baumé.

This extra thickening arrangement should not have been required if the washing train was set up properly. The problem was that the minimum liquid flow to carry the solids down the train occurred somewhere within the train and not at the end of it. Attempts to starve the system of wash liquid failed because this simply reduced liquid flows everywhere in proportion and it did not move the bottleneck but merely increased starch losses to overflow. Analysis of the system function with a mass balance simulator software revealed a simple remedy: more liquid added to the solids at the front of the train moved the point of thickest underflow to the end of the train. A corresponding reduction in wash liquid addition then brought the system underflow to the desired concentration level, thereby obviating the need for the additional thickening series.

### Washing train design recommendations

The counter-current washing trains installed in industry often represent the most complex parts of the overall processes and are often designed and operated at conditions far from optimum. Experimenting with and optimising such systems is difficult, particularly where there are no inter-stage sumps used and samples of the intermediate streams cannot easily be taken. It is, therefore, advantageous to use a computer model<sup>5</sup> to find out how such systems work and how they respond to operational or design changes.

The following recommendations may be drawn from the mass balance calculations performed on different possible scenarios encountered in industry. Consulting experience with several working systems in industry confirms the conclusions.

**The washing efficiency** of a counter-current washing train is primarily determined by the values and order of the flow ratios  $R_f$  used in the train, and by the number of stages employed. It is not affected by the supply rate of wash liquid, irrespective of whether the liquid comes in with the solids or through the wash liquid feed at the end of the train. The wash liquid supply only determines the concentration of the solids in the underflows in the different stages and overall.

**The wash liquid requirement** of a washing train designed for a given washing efficiency and maximum

underflow solids concentration anywhere in the train is also determined by the values and order of the flow ratios  $R_f$  and by the number of stages employed. Fewer stages require lower  $R_f$  ratios and greater wash liquid supplies if they are to achieve the same washing efficiency and to operate at the same maximum underflow solids concentration.

**Setting of the flow ratios** in the different stages is another important design consideration. Generally, washing efficiency is maximised by minimising the flow ratios in all stages. The solubles/wash system cannot, however, be considered in isolation. The transport of the solids along the washing train and the solids separation efficiency in the individual stages and overall, also have to be taken into account. The problem is that the effect of the flow ratio in each stage on the washing efficiency and on the separation of the solids is contradictory and the demands in the different stages are not equal. In the first stage of the washing train, for example, good separation efficiency for the solids is paramount because the stage has no protection of the overflow recycle like in the following stages. So that higher  $R_f$  ratio is needed here, giving lower washing efficiency in the stage. In the following stages the flow ratio can be gradually reduced because they have increasingly greater protection by the overflow recycles, with the last stage designed for the best washing efficiency because it can allow some solids to escape with so many recycles to return those solids to the train. The problem is, therefore, one of optimisation of a three-component separation system and today's computer technology allows us to do this well. Surprisingly, there are still many washing trains in operation where all stages are set at the same  $R_f$  ratios and, therefore, not operating at optimum performance. This is particularly important in wheat starch applications where the fine particles present make solids recovery a special challenge.

In order to be able to optimise the system, we have to know how the flow ratio affects the separation of the solids. In the case of hydrocyclones, the effect of the ratio is two-fold: increasing  $R_f$  leads to improvements to separation efficiency by the contribution of the splitting of the flow called "dead flux" and a further improvement is caused by the reduction in the crowding of the underflow orifice. Both of the effects can be described analytically for certain hydrocyclone geometries and the above-mentioned optimisation is therefore possible. The technical aspects of this are beyond the scope of this paper and the reader is referred elsewhere<sup>1,2</sup> for details. Generally, the best design of a counter-current washing train using hydrocyclones is such that the flow ratios decrease along the train, so that:

1. the overall solids recovery is high,
2. the solids concentration is always highest at the end of the train (i.e. in the system underflow),
3. the solute or light component concentration in system overflow is high,
4. the wash liquid requirement is low.

A final note regarding the pros and cons of using the intermediate sumps between the stages. The washing efficiency predictions we make when designing washing trains are simply based on the mixing and thickening ratios in all stages. This assumes that there is perfect mixing taking place and that the mass transfer of any solubles from the solids into the suspending liquid is complete. This is true for wheat starch where the solids are reasonably non-porous and enough time and shear are assumed to be available in the pipework and in the hydrocyclone so that no extra residence time needs to be provided in a feed sump before the hydrocyclone. One still encounters some starch washing trains with feed sumps, however, which then provide greater flexibility, control and accessibility for sampling than the fully enclosed 'plumbed-in' installations.

## Conclusions

The technology for processing of wheat starch with hydrocyclones dates back to or before the second world war and it has been gradually better understood and further developed since. We now know enough to be able to optimize the available systems so that we can achieve much improved plant performance. The present paper gives a summary of the available and installed systems, the reasons behind the choices made and further references for more technical detail. There are some software tools now available for the design of hydrocyclones and their networks, and for doing the complex mass balance calculations involved in counter-current washing<sup>5</sup>.

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