Developments with high grade continuous centrifugals

Entwicklungen bei kontinuierlichen Zentrifugen für Magmen hoher Reinheit

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Continuous centrifugals suitable for producing final product sugars have been developed over recent years and are finding increasing application in the production of cane raw sugar and other duties. This paper reviews the technology and contemplates the application of these machines to beet white sugar. An important point is the color difference between the sugar produced and the mother liquor, which is much lower in the present applications than in beet white sugar magmas.

Kontinuierliche Zentrifugen zur Gewinnung von verkaufsfähigen Zuckern sind in den letzten Jahren entwickelt worden. Sie finden zunehmenden Einsatz in der Rohrrohzuckerzentrifugation und teilweise in der Raffinationsindustrie. Die Arbeit stellt die Technologie vor und beschreibt die Anwendungsmöglichkeiten dieser Zentrifugen bei Weißzucker. Ein wichtiger Punkt ist die Farbdifferenz zwischen dem Muttersirup und dem erzeugten Zucker, die bei den bisherigen Anwendungen wesentlich geringer ist als bei Rüben-Weißzuckermagmen.

1 Introduction

For a number of years engineers have been working on modifications to standard continuous centrifugals to make them suitable for production of final soluble sugar. Much of this work has focused on reducing or eliminating crystal damage in order to produce an acceptable crystal quality. The objective has been to bring the advantages of low maintenance and continuous throughput to uses traditionally performed by batch centrifugals. Most of the high grade continuous centrifugals (HGCC) have been installed in cane sugar factories producing raw sugar, with Australia the most significant user of these centrifugals.

A number of manufacturers offer HGCC machines, notably STG-FCB, Silver-Weibull and Broadbent-NQEA. In the competitive centrifugal market it is likely that other manufacturers will follow and the potential customer will need to closely study the machines on offer to determine which is likely to give him the required performance with highest reliability and lowest total cost of ownership.

2 Design features

HGCC available have a number of common features:

- A steep basket, usually with the basket wall at 25° to the vertical
- Crystal deflectors and proprietary features to minimize crystal damage
- Lower rotational speeds than conventional continuous centrifugals at around 700–1300 min^{-1}
- Variable speed drives

The variable speed drive may not be required in all applications, it provides more flexibility but in many cases will be an additional variable for the operator to worry about. The crystal deflectors will not be discussed further as they are essentially curved baffles to deflect the crystals down out of the centrifugal casing without damaging the crystal. Each manufacturer would probably claim to have the best deflector but there is little or no objective evidence in the public domain.

A benefit of the lower rotational speeds used is that the power consumption of a HGCC can be around 1 kWh/t massecuite or below, rather than the 3 kWh/t of conventional continuous centrifugals.

2.1 Basket angle

The most significant difference between the HGCC and traditional continuous centrifugals for low grade products is the basket angle. At 25° this is steeper than the traditional 30° or 34° baskets, although FCB have offered a 28° basket for a number of years.

In a conical basket continuous centrifugal it is the basket angle which determines what proportion of the centrifugal acceleration is available to move the crystals up the screens and out of the basket. With a horizontal spinning disk all of the G force is applied to throw the crystal off the disk, in a vertical walled batch centrifugal basket (a 0° basket angle) the crystal is pinned to the wall by the G force and there is no force component trying to push the crystal up the basket.

Mathematically, the acceleration acting on a single crystal is given by $G \cdot \sin\beta$ where G is the centrifugal acceleration and β is the basket angle. The acceleration G (m/s^2) is equal to $r \cdot \omega^2$ where r is the basket radius (m) and ω is the basket rotational speed (rad/s).

Steeper baskets with lower values of β have lower acceleration acting on the crystals, similarly lower rotation speeds reduce the acceleration. Both of these features are employed in HGCCs.

Operating with a steeper basket and slower speed of rotation are not in themselves sufficient to give a radical change in the behaviour of crystals in the basket. The influence of friction is critical.

If sugar crystals are placed on a horizontal sheet of metal and the sheet inclined slowly upwards there will come a point where the crystals slide down the sheet. This happens when the friction between the crystals and the sheet are overcome by the component of gravity acting to push the crystals down the sheet.

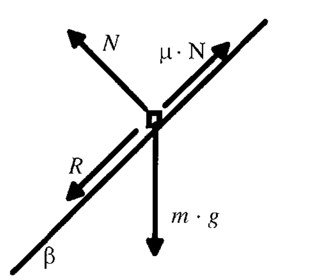

Fig 1: Force balance on a single crystal under gravity

In Figure 1 the force due to gravity $m \cdot g$ is acting vertically downwards on the crystal, this generates a normal reaction N perpendicular to the inclined sheet and hence a friction force $\mu \cdot N$ which opposes movement of the crystal down the sheet. The force R is a component of the gravitational force acting to slide the crystal down the sheet, its magnitude is $m \cdot g \cdot \sin\beta$.

The resulting force pushing the crystal down the sheet is $R - \mu \cdot N$ which expands out to:

Net motive force:
$m \cdot g \cdot \sin\beta - \mu \cdot m \cdot g \cdot \cos\beta = m \cdot g\,(\sin\beta - m \cdot \cos\beta)$

This net motive force becomes positive and the crystal starts to accelerate when the bracketed term exceeds zero, when $(\sin\beta - m \cdot \cos\beta) = 0$, i.e. when $\mu = \tan\beta$. In others words movement commenc-

es at the point where the tangent of the angle of inclination equals the coefficient of friction, this angle is termed the "critical angle".
The coefficient of friction for sugar crystals on metal is around 0.45, giving a critical angle of 24.2°. Angles greater than 24.2° will allow the sugar to slide at this coefficient of friction.
Using this inclined sheet analysis in a conical centrifugal basket gives Figure 2. Although the basket angle is expressed relative to the vertical the centrifugal force is at 90° to gravity and the analysis holds true:

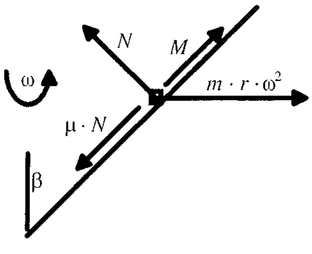

Fig. 2: Force balance on a single crystal in a centrifuge

Net acceleration force:
$M - \mu \cdot N = m \cdot r \cdot \omega^2 (\sin \beta - \mu \cdot \cos \beta)$
Sugar crystals will only move up the screen of a conical basket centrifuge if the angle of the basket to the vertical exceeds the critical angle for sugar on the screen, in other words the angle should be such that its tangent is greater than coefficient of friction.
The net acceleration force acting on a single crystal is given by

$m \cdot r \cdot \omega^2 (\sin \beta - \mu \cdot \cos \beta)$

and it is clear that the sign of this force is dependent on basket angle and coefficient of friction alone, the magnitude of the G force does not determine whether the crystals slide up the basket.
This is an important result which has been verified in laboratory tests with multiple basket angles – if the basket is too steep for the sugar/screen combination the sugar will stay in the basket and the crystals will grind to powder in the bottom of the basket.

2.2 Residence time

Where the basket angle is close to the critical angle of friction there will only be modest acceleration of the crystal. This is beneficial to the HGCC operation as the longer residence time that results improves purging and washing. There is also a direct benefit to crystal breakage of lower crystal velocity.
Calculating the residence time for single crystals may be misleading as there will be interaction with other crystals, with holes in the screen and with the wash water. It does however illustrate the relative effects of the different basket angles.

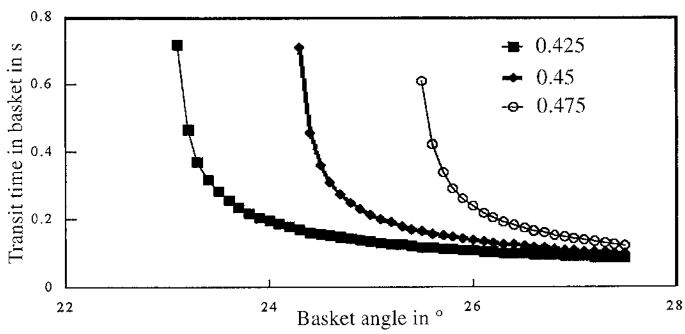

Fig 3: Single crystal residence time in s at different coefficients of friction
Based on: $G \leq 375$ m/s. Min basket diameter 0,6 m; max. basket disameter 1.2 m. (Broadbent Centrifuges 1994)

Similar mathematics can be used to compare different machines. A HGCC running at 900 min^{-1} with a 25° basket has a single crystal residence time 6 times greater than a 30° basket centrifugal running at 1800 min^{-1}, or 9 times greater than a 34° basket centrifugal running at 2000 min^{-1}.

Table 1: Theoretical single crystal residence time

Basket angle in °	Relative residence time
25	1
28	0.43
30	0.34
34	0.24

The different basket angles affect residence time independent of speed, for a given value of the friction factor (Table 1).
Although these extended residence times help syrup separation and washing one must not forget that the lower G forces implicit in lower speeds will provide a lower driving force for the removal of mother liquor from the sugar cake. Difficult separations may require high G forces which in turn means high rotational speeds and consequently short residence times.
The residence time increases dramatically as the basket angle approaches the critical angle for the sugar/screen combination. The ideal basket has an angle very close to the critical angle, in order to maximize residence time. The problem here is that a change in the coefficient of friction may result in sugar not travelling up the screen.

2.3 Crystal velocity

Velocity is the enemy of crystal quality as the kinetic energy of a high velocity crystal leaving a centrifugal basket will be dissipated by impacts with the centrifugal casing and other crystals. HGCC designs provide a gentle deflection path to minimize breakage and use low rotational speed and steep baskets to minimize crystal velocity.

Table 2: Crystal velocity along screen in m/s

	Basket angle	
Basket min^{-1}	25°	30°
900	8.2	20.6
1,800	16.4	41.2

Crystal velocity along the screen is proportional to the rotational speed, as shown in Table 2. Although the acceleration varies as the square of the rotational speed the time that the crystal is exposed to the acceleration decreases, resulting in a linear relationship. As the kinetic energy of the crystal varies with the square of the rotational velocity there is 6 times the kinetic energy in sugar leaving a 30° basket as there is with a 25° basket.
A similar effect is seen on the tangential velocity of crystals as they are flung off the basket lip:

Table 3: Tangential crystal velocity of sucrose crystals leaving the basket in m/s

Basket speed in min^{-1}	Basket top diameter, mm	
	1,072	1,144
900	51	54
1,800	101	108

3 Process performance

3.1 Overall performance

HGCCs are used to replace batch centrifugals in the production of cane A raw sugar and in this duty the product quality matches that of batch machines. A typical example would be production of 99.4% purity VHP raw sugar from massecuite of 84–86% purity at 25–35 t per h massecuite flow. Crystal damage is minimal with no significant differences between MA and CV of dried product sugar between the batch and continuous machines at the same factory.

All HGCC machines seem to share a number of characteristics:

- lower sugar purity at higher throughput
- increasing sugar water content with increasing throughput
- high wash water demand compared to batch centrifugals
- lower dry substance content of run-off syrup

Typical performance graphs are shown in Figures 4 and 5, illustrating the effect of wash water and throughput for cane A massecuite.

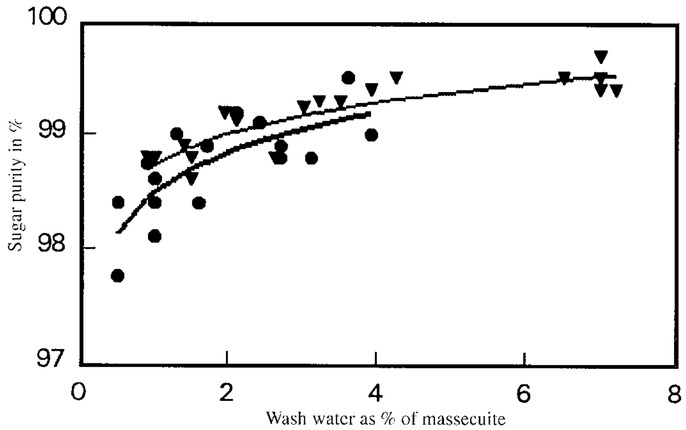

Fig 4: Typical HGCC performance curve – wash
A massecuite. ▼ 30 t/h massecuite; ● 45 t/h massecuite.
Source: *Kirby, L.; Greig, C..; Atherton, P.; White, E.; Murray, C.:* Int. Sugar J. 92, no. 1104

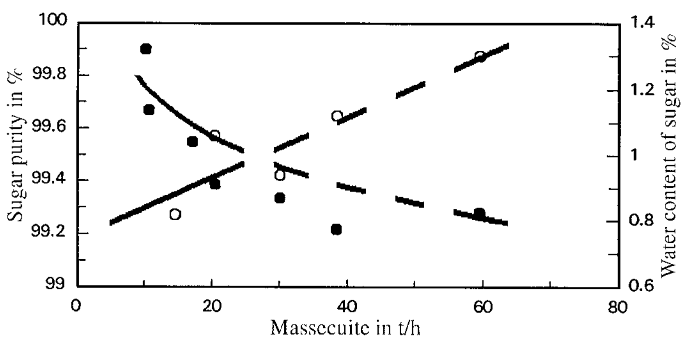

Fig 5: Typical HGCC performance data – throughput
● Sucrose content; ○ Water content
Operating speed 900–1100 min^{-1}. Sucrose content is corrected to 0% water content. Massecuite rate calculated from run-off syrup flow. Data are typical and depend on massecuite quality and temperature. (Broadbent Ltd., 1996)

The decline in performance and increase in moisture at higher throughputs can be attributed to the increasing thickness of the massecuite and sugar layers, with velocity of travel effectively fixed by the basket angle, rotational speed and coefficient of friction.

3.2 Washing

Achieving the required sugar quality by washing is more difficult in an HGCC than in a batch centrifugal, but easier than in a conventional high speed continuous centrifugal. A batch machine can consistently apply the wash water at a uniform rate to a static bed of sugar crystals of fixed thickness, whereas an HGCC has to contend with a moving bed of variable thickness and a short residence time.
One benefit of the thin layer and short contact time in an HGCC is the ability to apply large volumes of wash water without dissolving a lot of sugar. If an excessive wash water quantity is used the d.s. content of the run-off syrup produced will fall to 50% or below, indicating that the wash water has not been saturated by passing through the crystal layer.

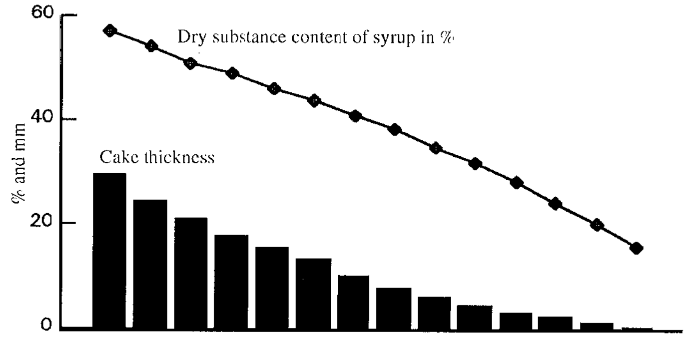

Fig 6: Syrup dry substance content, washing cake of declining thickness

This can be observed in laboratory work, washing cakes of declining thickness at constant wash rate in a batch centrifugal basket. Below 30 mm cake thickness the wash water dry substance content falls below 60%. When mixed in with the mother liquor the syrup leaving an HGCC tends to be 65–72% dry substance content.

3.3 Range of application

Not all duties are suitable for an HGCC. The additional costs of the crystal deflector and variable speed drive are only justifiable for use on sugars for sale or where crystal damage is important. Massecuites below 80% purity probably require a bigger *G* force for effective centrifuging than an HGCC can provide. Small crystals with sticky syrup coatings may have too high a coefficient of friction to move up a 25° basket.
Generally HGCC machines should be confined to massecuites over 80% purity which are centrifuged relatively easily. A minimum crystal size of perhaps 0.4 mm may also be advisable, although there is no evidence to support this as a firm rule.
In the beet industry the second product (raw / intermediate / high raw / B) massecuite is a suitable application, having similar purity levels to cane A massecuite with lower viscosity and (generally) higher temperature. White sugar is discussed further below.

4 A continuous white sugar centrifugal?

The continuous white sugar centrifugal may be something of a Holy Grail to the beet industry. It may or may not be possible to meet all the requirements with an HGCC. There are HGCCs in operation on refinery white sugar products, meeting the crystal breakage and other criteria. One has to compare different requirements for massecuite centrifugation in order to understand the relative difficulty.

4.1 Characterizing the duty

Table 4: Requirements for centrifugation of different massecuites

Duty	Product purity %	Run-off syrup purity %	Product color IU	Run-off Syrup color IU	Ratio
Cane A (VHP)	99.4	68	1,400	35,000	25
Beet raw (B)	>99	70	700	14,000	20
Beet white	>99.9	86	25	8,000	320
Refinery white	>99.9	>95	50	3,000	60

Comparing centrifugation of refinery white massecuite with beet white massecuite, the latter is aiming to produce the same or similar color sugar from a higher color lower purity massecuite. As the centrifugal has to separate the massecuite by a combination of centrifugal force and washing it is the amount of "residual syrup" remaining on the crystal that determines how difficult the duty is.
Centrifugation of beet white sugar is therefore more difficult than of refinery white sugar, as the ratio of run-off syrup color to product

color is much higher, around 300 IU compared with around 50. The VHP cane raw duty, which is carried out satisfactorily by HGCCs, has a ratio of around 25.

4.2 Residual syrup quantity

Knowledge of the distribution of nonsugars or color between the crystal lattice and the surface film may allow characterisation of the duties by the "residual syrup" remaining on the crystals after washing in the centrifugal.
In beet white sugar the whole sugar color is only 20–35% higher than the color of the crystal, determined by affination in a saturated solution. VHP cane raw sugars may have a whole color up to 80% higher than the crystal color, implying a greater quantity of syrup and / or a higher syrup color. Using these figures and data from Table 4 gives an estimate of the "residual syrup" quantity:

Table 5: Analysis of residual syrup of sugar crystals

	Whole color IU	Crystal color IU	Ratio	Syrup color IU	Residual syrup %
VHP raw	1,400	800	1.75	35,000	1.79
Beet white	24	18	1.33	8,000	0.08
Beet white	24	18	1.33	360	1.79

Table 5 illustrates the marked difference between VHP raw sugar and the beet white sugar, assuming that the residual syrup has the same color as the total run-off syrup leaving the centrifugal.
This is a potentially flawed analysis as the residual syrup clinging to the crystals will in reality be a mixture of mother liquor and dissolved crystals. As the proportion of dissolved crystal in this syrup is increased its color will decrease. The last line of Table 5 shows the syrup color that would be needed to achieve a normal beet white sugar color with a level of residual syrup equivalent to that in the VHP raw sugar from HGCC operation.
A color of 360 IU seems low compared to the high green run-off syrup color of 5–10,000, but is consistent with measured values from single batches of sugar in a large batch centrifugal. In the latter case syrup colors below 500 were measured during the last 40 seconds of syrup runoff.
The conclusion one draws from this is that a certain amount of crystal dissolution may be required in order to produce a residual syrup of sufficiently high quality to allow product quality specifications to be met. In other words to reduce the impurities (color) to an acceptable level one has to dissolve some of the product to provide a displacement syrup.
The authors are currently not in a position to say whether the short residence time of a continuous centrifugal will be sufficient to allow this product dissolution to occur. The fact that HGCCs can match batch machines on product quality for VHP raw sugars suggests it may be possible.

5 Conclusions

High grade continuous centrifugals are becoming common in the production of cane raw sugars, meeting all product quality requirements including crystal breakage.
A number of beet applications are also possible, where higher purities and larger crystals facilitate the use of steep 25° baskets.
The application of HGCC machines to refinery granulated sugar suggests that use for beet white sugar massecuites may be feasible, although the high ratio of syrup color to product color dictates a low level of residual syrup. This may not be achievable without some product dissolution and this may not be practical within the short residence time of an HGCC. More work is required in this area.
Where the HGCC is suitable it offers lower power consumption than traditional continuous centrifugals plus the usual benefits of continuous smooth running. The price of these benefits is a higher sugar water content and a higher wash water consumption.
Where product quality is very high and energy costs high the modern inverter driven batch centrifugal could continue to be the machine of choice.

Développements dans les centrifuges continues pour produits de haute qualité (Résumé)

Les centrifuges continues convenant pour la production de sucre commercialisable se sont développées ces dernières années et trouvent de nouvelles applications pour la production de sucre brut de canne ainsi que dans d'autres domaines.
Cet article passe en revue la technologie et considère l'application de ces machines pour le sucre blanc de betteraves. Un point important c'est la différence de coloration entre le sucre produit et l'égoutmère qui est beaucoup plus basse dans les applications actuelles que dans les magmas de sucre blanc de betteraves.

Desarrollos en centrífugas continuas para magmas de altas purezas (Resumen)

En los últimos años se desarrollaron centrífugas continuas para la producción de azúcares de alta calidad. Más y más se emplean estas centrífugas en la centrifugación del azúcar crudo de caña y en la industria de refinación. En este trabajo se presenta, por uno, la tecnología y se describe, por otro, las posibilidades del empleo de estas centrífugas a nivel del azúcar blanco. Un punto muy importante es la diferencia de color entre el jarabe madre y el azúcar producido, diferencia que es claramente menor en las aplicaciones actuales que en magmas de azúcar blanco de remolachas.

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