Batch centrifuge basket design.

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1. Abstract.

A short overview of batch centrifuge basket design is presented with reference to process performance, efficiency, perforation type, safety and cost. The mechanical loads supported by the basket during normal operation and aspects such as perforation type, use of re-enforcing hoops and materials of construction are discussed. The requirements for on-going inspection and maintenance of baskets is emphasised.

2. Introduction.

The design of centrifuges used within the European Economic Area is subject to the requirements laid down in the type C standard EN12547-2014 “Centrifuges – Common safety requirements” [Ref 1]. This standard covers many aspects of centrifuge design however a large part relates to the safety requirements, protective measures and verification of mechanical hazards associated with the ejection of parts from the rotating centrifuge basket.

Given the potential risks associated with a poorly designed centrifuge basket this focus on safety and protective measures is understandable and consequently Broadbent manufacture all baskets to exceed the EN12547 standard regardless of their final location.

A typical batch centrifuge used for sugar production with a basket capacity of 1.75 tonnes of massecuite per charge has a stored energy of approximately 7 MJ at a spin speed of 1100 rpm. This is equivalent to a 1.5 tonne car travelling at 200 mph (320 kph). If this energy were to be released in an uncontrolled way a significant amount of damage is inevitable with possible fatal injury to individuals close at hand. It is a common misconception that the outer casing of a sugar batch centrifugal will contain a basket that ruptures; to have a reasonable chance of containment the outer casing would need to be in the region 20-30mm thick.

In addition to the obvious need for safety there are also requirements for good process performance, low basket cost and high process and energy efficiency. Any final design being a balance of these generally competing requirements – with the overriding requirement being safety.

The high throughput of batch centrifuges used in the sugar industry poses an additional problem for designers. The excellent filterability of good sugar massecuite allow centrifuges to operate with fast cycling rates of up to 30 cycles per hour. Some beet and most refineries operate in excess of 7500 hours per year, and over an assumed life of 20 years the centrifugal basket will therefore experience over 3 million cycles, which in turn means the designer must guard against catastrophic failure from metal fatigue caused by the cyclic stresses experienced by the basket.
3. Design procedure.

A good understanding of the loads encountered by the basket during operation is a necessary first step in the design process. The basket is subjected to a variety of loads during operation and full analysis requires a detailed investigation of all possible loads. In this short overview some aspects of the following loads are considered:

- Loads due to centrifugal force acting on the self-weight of the basket.
- Loads due to centrifugal force acting on the product in the basket (i.e. massecuite).
- Loads due to centrifugal force acting on any unbalance within the basket.

3.1 Centrifugal loads due to the self-weight of the basket.

The loads on an empty basket are due solely to the self-weight of the basket. If any residual stresses in the basket material are ignored then the stresses in a stationary basket are very near zero. Once the basket starts to rotate the circumferential stresses $\sigma$ in the basket wall (comprising shell plus hoops if fitted) increase and are related to basket diameter $D$ and centrifugal $G$ (where $1G = 9.81\text{m/s}^2$) by Eqn 1:

$$\sigma \propto G D$$  \hspace{1cm} (1)

This shows that for a given $G$ basket circumferential stress $\sigma$ increases linearly with basket diameter $D$ and this has the effect of limiting the maximum diameter of a basket. Typically approximately 50% of the allowable maximum stress levels in the basket wall (shell plus hoops if fitted) are taken up supporting the basket self-weight, leaving the remaining 50% to provide support for the massecuite load within the basket. The larger the basket diameter the greater proportion used to support the basket self-weight leaving less to support the massecuite.
3.2 Centrifugal loads on the basket from the product.

The addition of massecuite in the basket increases the mass to be supported and therefore the stress in the basket material. The circumferential stress in the basket wall increases in proportion to the additional massecuite load, however at the top and bottom of the basket the situation is more complex. Figure 2 shows the pressure distribution caused by the massecuite. This upward pressure is resisted by the top lip of the basket creating a complex stress distribution in the region where the top attaches to the basket shell.

*Figure 2. Pressure distribution on basket top.*

The stress distribution is further complicated by the restraining effect of the basket top on the basket shell. The combination of the pressure distribution and restraining effect can be seen in figure 3 which shows the deformed shape of the top half of a basket at spin speed.

*Figure 3. Deformation (100x actual) for typical basket.*
3.3 Unbalance forces on the basket.

It is important that the basket is designed to accommodate out-of-balance loads. Normally these are limited to a small fraction of the massecuite load and the vibration that results if the out-of-balance limit is exceeded can be detected by the control system and remedial action taken. Figure 4 shows the deformed shape of a basket with a 10kg out of balance at 1,100 G which generates an out-of-balance force of 11 tonnes and results in a basket deformation adjacent to the out of balance of approximately 4mm.

*Figure 4. Deformation (50x actual) for basket with 10kg OOB.*

3.4 Basket perforations.

A complicating factor in basket design is the need for perforations to allow the mother liquor (molasses) to drain from the centrifuged cake. As is well known, the placement of a hole in a uniformly stressed sheet of material increases the stresses local to the hole [Ref 2]. For the case of a 6mm diameter circular hole in the shell of a typical centrifuge basket the stress next to the hole is 2.7 times greater than the stress distant from the hole. This effect is shown in figure 5.

*Figure 5. Stress concentration due to circular hole.*
The designer must account for this increased level of stress when designing the basket, and as can be seen from figure 5 the effect is significant. The shape of the hole has a significant effect of the stress concentration factor. For an ellipse (20 x 6mm) with the stress acting parallel to the long axis the stress concentration reduces to 1.7, however if there is some stress acting perpendicular to the long axis of the ellipse, as might be the case adjacent to the top or bottom of the basket, the stress concentration increases to 6.7 (see figure 6).

![Figure 6. Stress concentrations due to ellipse.](image)

(a) Stress parallel to long axis.  (b) Perpendicular to the long axis.

The number of perforations has an impact on process performance. Too few and the massecuite purging is restricted limiting the throughput of the centrifuge; too many and the basket cost is increased. The method of forming the perforation is also important. Any tearing or melting of the material during the process of forming the perforations (e.g. punching or laser cutting rather than drilling) will further increase the residual stress levels around the perforations. Drilling the perforation in a flat sheet of steel, then rolling it in to a cylinder to produce the basket shell also increases the residual stresses local to the perforations. Finally it is important not to perforate the shell close to the seam weld in the shell material.

3.5 Hooped basket vs. un-hooped.

There are two common methods of manufacture of basket shells (see figure 1). One uses a plain shell, the other has additional re-enforcing hoops fitted to assist in supporting the shell; both types are common in the sugar industry. It should be noted that for a basket with a plain shell (i.e. no hoops) it is the shell, with its stress concentrating perforations, which must support all the loads, self-weight (section 3.1) and massecuite (section 3.2).

In the alternative case of a shell with additional re-enforcing hoops there are no stress concentrating perforations in the hoops and this allows them to carry higher stresses, thereby reducing the amount of material necessary to support the load. As might be
expected the hooped basket has a lower mass and inertia so requires less energy to accelerate it to spin speed.

Hooped baskets are usually designed to avoid failure in the event of loss of a single hoop. Likewise if the shell fails the hoops are designed to carry the total load for a short period thereby maintaining the basket integrity. The situation for an un-hooped basket is different; failure of the shell is very likely to result in immediate total failure of the basket.

Hooped baskets therefore have the potential to deliver the lowest inertia whilst providing the greater resilience against failure, both of which are significant benefits. The downside of hooped basket is that they are more expensive to manufacture. Broadbent manufacture both hooped and un-hooped baskets (see figure 1), but for high cycling duties such as sugar production Broadbent’s standard policy is to offer baskets fitted with re-enforcing hoops.


Baskets are normally manufactured from standard high strength carbon steels, austenitic or duplex stainless steel and their cast equivalents. The centrifuge standard EN12547:2014 provides details of suitable methods for calculating the strength of the basket and maximum allowable stresses for ‘steady’ (i.e. non-cyclic) loading. However as outlined in section 2 cyclic loading dominates in the sugar application and therefore design methods considering only steady loading are unsuitable.

The centrifuge standard requires that the ‘rotor (i.e. basket) shall be designed with a safety margin against fatigue failure’ and the ‘load and expected number of cycles shall be assessed to determine if this will lead to fatigue failure during the foreseeable life of the centrifuge’. [Ref 1 section 5.2.1.1].

Given that the basket will be subjected to a million or more stress cycles during its lifetime, the requirement in the standard is clearly sensible. The basket should be designed for a long life taking full account of the fatigue properties of the materials of construction and the level of cyclic stresses expected within the basket.

The ability of a material to resist fatigue failure depends on the type of loading. For example the fatigue resistance of a given material to a reversing stress of +/- $\sigma$ differs from a stress going from zero to $2\sigma$. Most published data is based on alternating +/-$\sigma$ tests which is not truly representative of centrifuge basket loading. In order to obtain accurate fatigue life data for a particular material it is necessary to conduct tests to ascertain the fatigue life with mean and alternating stresses representative of the loadings found in batch centrifuge baskets.

As a general rule ferrous materials will not fail by fatigue if the stress is kept below a certain value known as the fatigue limit, which averages at about 50% of the ultimate tensile strength (UTS). Figure 7 shows the typical variation of fatigue strength (S) with stress cycles (N) together with the fatigue limit for N>10⁶ cycles.
It might be thought that fatigue could be avoided by simply using a stronger material. However as the UTS increases the fatigue limit as a percentage of the UTS drops (see figure 8) and there is no benefit in using the higher strength material with a UTS above 1200 MPa.

**Figure 7. Variation of fatigue limit with number of stress cycles.**

![Typical S-N curve for wrought ferrous material UTS < 1200MPa](image)

**Figure 8. Variation of fatigue limit with UTS for a wide range of steels. [Ref 3].**

![Fatigue limit vs UTS graph](image)

5. **Maintenance and inspection.**

However vigilant the designer and manufacturer are in their efforts to produce a basket with infinite life the possibility of failure always remains. Other than design or manufacturing problems, failure may occur due to a variety of other factors including:
- Mechanical handling damage.
- Unsuitable repairs or welding on the basket.
- Severe out-of-balance events during centrifuge operation.
- Corrosion caused by chemicals used in the sugar manufacturing process (e.g. ion exchange reagents) or present in the agricultural environment in which the beet/cane is grown (e.g. salt in coastal regions).

To help avoid such problems the user should always perform routine inspections on the basket and other critical components as recommended by the original equipment manufacturer. Such inspections are usually required at regular intervals, typically 12 months. Basket failures are very rare, however those few that do occur are highly likely to be the result of fatigue. It can take many centrifuge stress cycles before a crack nucleates and grows to a size where it becomes detectable, and many more cycles before it grows to the point where fast fracture occurs and the basket fails potentially catastrophically.

As part of the design process it is possible to estimate the number of stress cycle required to grow a crack from a given size to the point where fast fracture will occur [Ref 4]. If it is further assumed that inspection techniques used on the basket can reliably detect cracks of length 1mm or above then the period between inspections should be less than the time it takes for the pre-existing 1mm crack to grow to the point where failure occurs. Figure 9 shows an example of the estimated growth rate of a 1mm pre-existing crack; when the crack grows to a length of approximately 35mm fast fracture occurs and the basket fails.

*Figure 9. Crack growth rates showing the number of cycle to failure.*

For this case it takes just under 200,000 cycles for the crack to grow to failure, which is more than 12 months operation in a sugar refinery operating 24 hours per day for 365 days per year. So if the initial crack appeared one day after an inspection, the crack should not have grown to the failure point after 12 months, when the next inspection is due.
It is important to understand that the period between inspections (typically one year) should never be lengthened simply because all previous inspections have not revealed a problem. In fact the older a basket gets the more important the future inspections become.


Batch centrifuge baskets are complex items and some of the complexities are considered in the preceding sections. The key issues discussed in relation to low inertia, good process performance and long term safe and reliable operation are:

- The cyclic loading experienced by the basket.
- The stress concentrations caused by the basket perforations.
- The fatigue properties of basket material.
- The additional safety and lower inertia afforded by the use of re-enforcing hoops.
- A good understanding of the need for regular inspections and approved maintenance procedures.

Careful design, manufacture and adherence to inspection routines provide the basis for trouble free long term safe operation, as demonstrated by the many thousands of centrifuge baskets in operation in the sugar industry worldwide.

7. References.