Recent developments in vertical cooling crystalliser design

In modern installations vertical cooling crystallisers are now preferred over traditional horizontal units because of the significant benefits they offer, which include larger volumes and smaller footprint, suitability for outdoor installation, higher cooling surface to volume ratios and a better ability to handle highly viscous massecuite, amongst others. Since the first vertical cooling crystallisers were introduced, nearly 40 years ago, there has been a steady increase in their unit size from initial volumes in the 50–200 m³ range up to the present day where the most general unit size is now in the 300–400 m³ range, with even larger units becoming increasingly common. Large crystallisers present some significant design challenges and a good modern vertical cooling crystalliser design requires a robust construction of heat exchange surface, stirrer and drive units coupled with features that promote good heat transfer characteristics and uniform massecuite flow patterns. Careful attention to cooling tube and stirrer arm design and configuration are needed to achieve this, whilst the use of modern planetary gearboxes and variable frequency controlled motor drive units can provide added benefits to boost both performance and reliability. How these design features are incorporated in a modern unit is explained, focusing on cane C massecuite duty and using the Fives Cail and Fives Fletcher units as an example.

Key words: cooling crystalliser, vertical, cooling, stirrer, massecuite, viscosity

1 Introduction

- Additional massecuite exhaustion that can be achieved through cooling and mixing massecuite discharged from an evaporating crystalliser (vacuum pan) in cooling crystallisers is both significant and valuable. It is of particular importance for C massecuites, in order to ensure that the lowest possible molasses purity is obtained. For cane C massecuites a mother liquor purity drop of between six and eight units can usually be achieved.

For modern installations vertical cooling crystallisers are the preferred choice, over horizontal units, for the following main reasons (Hugot, 1986; Rein, 2007):
- They can be made larger and have smaller footprint requirements.
- They do not require supporting steel work and are suitable for outdoor installation.
- They can have higher cooling surface to volume (S/V) ratios and have a better ability to handle viscous massecuite.
- They do not have shaft glands that can leak massecuite.
- They are cheaper to install than the equivalent capacity of horizontal units.
- They provide an easier and more efficient facility for storing massecuite for extended periods of time (i.e. over an off-season). Vertical cooling crystallisers have now been used in both the beet and cane sugar industries for over 40 years (van der Poel et al., 1998). During this time there has been a significant enlargement in the unit size of vertical cooling crystallisers from, initially, volumes in the 50–200 m³ range up to the present day where the most general unit size is now in the
A considerable number of different vertical cooling crystalliser designs have been proposed and installed and a significant number of these have not been successful, with inadequate drives and massecuite short-circuiting being the most common problems (Rein, 2007). To achieve good crystallisation it is necessary to have crystallisers with sufficient retention time, good flow patterns (i.e. close approach to plug flow) and sufficient cooling (Love, 2010). Poor crystalliser designs and stirrer malfunction will lead to channelled massecuite and the creation of dead volume causing a reduced purity drop in the mother liquor, as will poor cooling due to either inferior equipment design or operational problems. Similarly, lower purity drops will be obtained if the massecuite dry substance or degree of cooling has to be restricted because of equipment limitations. It underlines the importance of having both well-designed and properly operated equipment and highlights the significant design challenges that large modern vertical cooling crystallisers present.

Design aspects that have to be considered with vertical cooling crystallisers are:
- Vessel diameter and height;
- Cooling surface configuration;
- Agitator configuration;
- Agitator drive selection;
- Flow paths for massecuite and cooling water.

Each of these points discussed in the following sections with specific reference to the design choices adopted for the Fives Fletcher (FF) vertical cooling crystallisers. The essential design approach has been to make them as efficient, robust and as simple as possible.

2 Vessel diameter and height

Selecting the vessel diameter and height to be used requires evaluating the relative merits between a tall narrow vessel and a shorter squatter shape. The range of diameters for vertical cooling crystallisers used by equipment suppliers varies from 3 to 8 m with heights ranging from eight to >30 m. Intuitively a long narrow crystalliser should give a better flow pattern but will be more expensive to make than one which is wider and shorter.

Long narrow vessels will require a higher stirrer rotational speed to obtain the same stirrer tip speed. Lower shorter stirrer arms will reduce the stirrer torque load, at the expense of decreasing the cross-section area, which in turn increases the massecuite velocity through the vessel. Experience has shown that too high a velocity can contribute to a high pressure drop across the vessel. The higher the aspect (height/diameter) ratio the higher will be the equipment and installation cost as, not only is more material required (due to a higher shell surface area per unit volume), there is also an increase in the fabrication work involved due to the additional banks of tubes required. Lower massecuite and water pumps will also have to deliver at higher pressures. On the other hand, large diameter vertical cooling crystallisers with low aspect ratios will require higher stirrer torque loads, have a greater potential for massecuite short circuiting and dead volume creation and consequently give poorer performances.

Fives Call and Fives Fletcher currently use three standard diameters of 4.5, 5.25 and 5.75 m, with shell heights ranging from 12 to 24 m giving vertical cooling crystallisers with volumetric capacities ranging from 150 to 500 m³. This gives aspect ratios ranging from 5.0 down to 2.5 as a minimum, which is considered as the best compromise between the conflicting ‘narrow and thin’ versus ‘short and squat’ shape requirements.

3 Cooling surface configuration

Whilst some level of cooling in vertical cooling crystallisers can take place through the shell the major portion is accomplished by cooling water flowing through dedicated elements. In order to simplify design calculations it is assumed that the heat loss through the shell is balanced by the heat input imparted to the massecuite from the stirrer, which therefore enables these factors to be ignored in cooling surface design calculations. The cooling water flow rate through each crystalliser for simplicity should preferably be a single pass, and arranged to be counter-current to the massecuite flow.

3.1 Moving versus static cooling elements.

Crystalliser cooling elements can be either static or configured as moving elements functioning as both agitation and cooling devices. Moving cooling elements can be constructed as either oscillating or rotating units. The use of hydraulic rams to oscillate cooling element vertically within the body of massecuite was first applied in crystallisers used in Mexico, called Crista Churn. This design has some advantage for very large crystallisers as it avoids the requirement for a large motor and gearbox drive unit with very high torque ratings. However, it is a more complex design and the cooling elements are subjected
to higher cyclic mechanical stresses. Another disadvantage is that the direction of the agitation is in-line with the massecuite flow, rather than being perpendicular to it which is, as explained later, an important feature required for preventing massecuite short-circuiting.

A number of different forms of rotating cooling elements have been tested. These include discs or plates, nipped elements, and plain tubes. In general moving cooling elements have the following disadvantages when compared with fixed cooling elements:

- Getting cooling water into and out of the elements is complicated and often results in leaks and spillages.
- The cooling elements are subjected to higher mechanical stresses which can result, in time, with fatigue cracks forming at the weld joints.
- In order to drain cooling water from the cooling elements it is necessary to first empty the massecuite out of the crystallisers.
- The overall system is more complex than a well designed system of fixed elements.

### 3.2 Static cooling elements

Mainly for the reasons mentioned above, fixed or static cooling surfaces are more commonly used in modern large vertical cooling crystallisers. These elements also come in a number of different forms (such as disks, plates, plain and nipped tubes etc.) with plain tubes being the most commonly used type of element. In principal a small tube diameter should be advantageous as it should be easier to move cooled massecuite away from the tube surface. However, smaller diameter tubes, being more flexible, are less robust and require longer lengths to make up the surface area. A is increase in tube length, which is required to be added to each bank gives a greater restriction to the massecuite flow, and can become a particular problem with heavy C' cane massecuites. A smaller tube diameters can also result in much higher water pressure drops in large crystallisers operating with full counter current flow.

These tube banks can be arranged in a spiral form or as straight, horizontal tubes. Banks comprising straight, horizontal tubes are the most common. A common arrangement is shown in Figure 2, with each alternate tube bank arranged at right angles to the previous one. To optimise the heating surface, several manufacturers use pipes of 40 to 50 mm diameter, and 180° standard bends, which can give rise to high pressure drops across the element bank when handling very viscous massecuites. With this type of tube bank arrangement any weld leaks on the tube element joints requires the vessel to be emptied to both end and repair the leak and removing a tube becomes a major exercise. Other disadvantages of this type of tube bank configuration is that the stirrer arms will have to be attached after the main shaft has been installed (see Fig. 4), or else with some modified configurations the shaft has to be rotated on a series of 90° angle movements as the shaft is lowered in.

### 3.3 Cooling element design for vertical cooling crystallisers

In keeping with the philosophy of maintaining an efficient, simple and robust design static cooling elements comprising large diameter (consequently strong) tubes passing right through the shell are employed. This means the shell provides support for the tubes and the tubes provide extra strength and rigidity to the shell. This is also means an return bends can be mounted outside the shell thereby eliminating any internal welds or joints, and so reduces the risks of water leaks from faulty welded joints being able enter the massecuite. It also allows tubes to be easily isolated or replaced from the outside. A large diameter tubes give lower pressure drops through the cooling water system and also enable larger pitching between tubes to be used; thereby giving reduced pressure loss for the massecuite flow through the crystalliser. This tub layout design also give a greater choice of cooling surface to volume (S/V) ratios that can be employed and by changing the tube pitching and tube diameter S/V ratios ranging from 1.0 to 2.0 m⁻¹ can be obtained. Most other designs of vertical crystallisers with static cooling elements are restricted to a maximum value of around 1.6 m⁻¹ for their S/V ratios.
3.4 Cooling objectives and constraints

Cane C massecuites are normally delivered to vertical cooling crystallisers, from evaporating crystallisers (vacuum pans) or strike receivers, at temperatures varying from 70 to 65 °C. A massecuite is then typically cooled down to temperatures varying from 45 to 40 °C. Rein (2007) reports that residence times of 45 hours are often provided for cane C massecuite crystallisers. Pilot plant studies (Steindl et al., 2001) carried out by the Sugar Research Institute (SRI) found mother liquor purities continued to drop significantly with increasing residence times up to 30 h, following which there was a slower drop up to 45–48 h and virtually no further purity drop after this. A standard residence time values used for designing C crystalliser installations are from 35 to 40 h.

The range of heat transfer coefficients for cane C massecuite cooling that is reported in published literature is large. This can be explained by the large effect of the massecuite being processed exerts on the heat transfer coefficient. With low dry substance, high temperature, low viscosity massecuites the heat transfer coefficients can be orders of magnitude higher than those obtained with high dry substance, cooler and more viscous massecuites. Rein (2007) has produced a table with values obtained from a variety of sources, ranging from a minimum of 12 up to 81 W/(m²·K), with mean values ranging from 15 to 29 W/(m²·K). Of course cooling surface design and the amount of shear being achieved by the agitators are also important factors affecting the heat transfer coefficient. Values ranging from 16 to 20 W/(m²·K) are used for general design purposes.

For typical design conditions (i.e. cooling in vertical crystallisers from 70 to 65 °C down 45 to 40 °C with retention times of 35 to 40 hours) the average massecuite cooling rates will range from 0.5 to 0.9 K/h. However, in many situations vertical cooling crystalliser are added as supplementary units to an existing installation where the cooling is not efficient and for this reason a higher rate of cooling may then be required. The highest overall massecuite cooling rate recently designed for a cane C massecuite vertical cooling crystalliser installation is 1.3 K/h. Table 1 (Cases 1 and 2) gives some details of the cooling surface to volume ratios required to achieve the cooling rates mentioned above based on some typical heat transfer coefficients. Compared with general cooling rates reported in the literature the cooling rates described above are low. Moreover, a number of authors (Rein, 1980; Lionnet and Rein, 1980; Steindl et al., 2001) have highlighted the importance of maximising the initial cooling rates (to rates above 1.3 K/h). In vertical cooling crystallisers with counter current cooling water circuits the high temperatures and low viscosity of the massecuite at, and soon after, entry means the heat transfer coefficient will be substantially higher than the average and consequently much higher cooling rates are in fact achieved. Case 3 in Table 1 gives examples of initial cooling rates (over the first 12 hours) that could be expected for various S/V ratio and highlights the importance of having a generous S/V ratio so as to get a maximised initial cooling rate.

4 Agitator configuration

Studies and CFD modelling (McBain et al., 2002) have shown that stirring in vertical cooling crystallisers is important for breaking up thermal wakes and creating a uniform temperature field between cooling tube banks. It is creation of a uniform temperature field helps to avoid heat transfer from being wasted on already cooled massecuite and to eliminate excessively hot or cold regions. It is thus helps to improve both heat transfer and prevent short circuiting but, in order to achieve this breaking up of the thermal wakes the stirring action must be perpendicular to the isotherms (McBain et al., 2002).

There are two different stirring concepts used for agitator arm design. The most commonly adopted one aims to achieve a ploughing action close to the cooling elements to attempt to sweep away massecuite local to the elements. Stirrer arms are mounted as close to the cooling surfaces as practical without making contact. Their arms themselves are generally made from angle iron that is normally shaped to take the form of a rectangular box, aiming to wipe both the element above and below the stirrer arms and the side walls (see Fig. 4 which shows a stirrer and tube banks being fitted into a crystalliser vessel).

Keast and Sichter (1984) have reported on an evaluation that involved reducing the clearance between the stirrer arms and cooling elements from 10 to 5 mm to 2.5 mm. It was found that this had no significant effect on the heat transfer coefficients. It has been surmised that scraper type stirrers with a sweeping action close to the cooling element can create a stirring action essentially parallel to the cooling element and isothermal surfaces and so make the stirring ineffectual in breaking up the thermal wakes and the re-establishment of uniform temperature fields.

Another stirrer design concept is based on the use of the considerable drag developed by passing a solid object through a very viscous medium to create a shearing action above and below the stirrer arms and the cooled cooling elements. It is concept, used in stirrers by Fletcher Smith, is the one demonstrable.

| Table 1: Effect of S/V ratio and heat transfer coefficient on massecuite cooling rates in a vertical crystalliser |

<table>
<thead>
<tr>
<th>Coolant water temperature: 32 °C</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massecuite temperature in °C</td>
<td>65</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Massecuite temperature out in °C</td>
<td>45</td>
<td>40</td>
<td>55</td>
</tr>
<tr>
<td>Massecuite retention time in h</td>
<td>40</td>
<td>35</td>
<td>12</td>
</tr>
<tr>
<td>Massecuite cooling rate in k/h</td>
<td>0.5</td>
<td>0.9</td>
<td>1.3</td>
</tr>
<tr>
<td>Heat transfer coefficient in W/(m²·K)</td>
<td>16</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Required S/V ratio in m³</td>
<td>0.9</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>0.7</td>
<td>1.5</td>
<td>1.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>
5.1 Hydraulic drives

All hydraulic arrangements require a hydraulic pump pack and a hydraulic drive mechanism. A single pump pack can be designed to operate several crystallisers. Some installations operate with hydraulic motors mounted directly onto the drive shaft, but, because of the large size of hydraulic motors required for the high torques and low speeds this is not a common arrangement. Ratchet type drive mechanisms have been used with varying degrees of success, and although relatively cheap to manufacture, they require a fair amount of maintenance. Hydraulic drives, in general, have a reputation for being relatively complicated and difficult to maintain and because of these maintenance issues and the oil leak problems which can arise when they begin to wear, they are unpopular with many factories.

5.2 Electric motor drives with gear reducers

The use of an electric motor driving through a gear reducer provides a simple and reliable solution for turning crystalliser agitators and hence is the most commonly used method. The earliest drives generally all used the simple worm and wheel reducer for the final reduction stage. In these installations the speed reduction ranges from 70:85:1 and as the output speed is extremely slow, cast iron wheels have normally been used. This type of drive has the advantage of simplicity, the opportunity for local manufacturing and the ability to withstand fairly large occasional peak loads. However, for larger vertical cooling crystallisers requiring higher drive power input, the crown wheel sizes have in some installations become quite large. In these cases there is the danger that, if the massecuite becomes overcooled for any reason and the stirrer load rises to abnormal levels, the lubrication film at the teeth contact area can break down. This then gives rise to rapid wear, in turn requiring premature replacement of the worm and wheel units and in some extreme cases this situation has led to a failure of the gears in operation.

With the primary aim of avoiding this type of problem Fives Cail and Fives Fletcher have, in recent times, switched to using modern planetary gear reducers for this duty. Compared with
the traditional worm and crown wheel systems these reducers not only have an increased mechanical reliability, being integral shaft-mounted units they are more compact and have no alignment issues. The other great advantage of this type of reducer is their high mechanical efficiency, allowing a smaller drive to be installed.

Whilst the mechanical reliability of this type of drive is very good they do have the disadvantage of requiring a very high standard of mechanical maintenance that may entail specialist or manufacturer support if any fault develops. Therefore, in order to provide the highest degree of protection, variable frequency drives (VFD) systems with these reducers are preferred that have a programmed torque limiting control to safeguard against overload conditions. In the event that the design torque limits are approached, the inverter will automatically slow down to keep the shaft torque below the upper limit.

With this control as the starting point further enhancements were added which include using the torque signal to provide an output value that is used to set the cooling water temperature set-point. This then enables the cooling profile and stirrer speed to be set to a specific philosophy according to the consistency (i.e. dry substance content, viscosity etc.) of the massecuite being processed. Initially the input control parameter is based on maximising both cooling rate and shear imparted by the stirrer to the massecuite. Should there then be an increase in massecuite consistency, the control passes through a zone where the degree of cooling is maximised at a constant speed and then finally, if the massecuite consistency reaches abnormally high levels, the drive enters a band where the stirrer speed is reduced to limit the torque on the drive.

The important effect that maximising shear (or in effect stirrer speed) has on achieving the highest level of massecuite exhaustion in a crystalliser has been highlighted by a number of studies, including those of Rein (1980) and Steindl et al (2001). The latest planetary gear reducers, variable frequency drives and associated control philosophy have been used to maximise the shear through all the operating conditions. A system was designed, which has the capability not only to slow the stirrer speed to limit the torque for drive protection, but to also enable the system to maintain maximum permissible torque values, by allowing the stirrer speeds to be increased from a nominal 0.3 min$^{-1}$ up to 0.5 min$^{-1}$. Figure 7 shows a control system screen for a vertical crystalliser using this control scheme.

6 Flow path
6.1 Massecuite flow path

The difficulty of achieving a good continuous crystalliser flow pattern has been highlighted by Love (2001). He explains that
this is because cooling of a massecuite stream which allows alternate flow paths to develop is inherently unstable. It is because on the one hand a cooled massecuite flow path becomes more viscous resulting in a reduced flow and then further cooling, whilst the hotter massecuite being less viscous flows faster which exacerbates any tendency for the formation of dead spots and short-circuits. Influence and interaction that a vertical crystalliser features, such as vessel shape, the design of the cooling elements and the effectiveness of the stirring action, have on achieving a good massecuite flow path and cooling efficiency has already been explained. Use of baffles to help direct the flow and prevent preferential flow path and bypassing is the main feature that vertical cooling crystallisers of Fletcher Smith employ for promoting the best possible flow paths.

Whilst the success of all these design features, with respect to cooling, can be seen in the performance results achieved it is difficult to rigorously determine the exhaustion performances, because of the varying nature of the massecuite being processed. Love (2001) has noted that using tracer tests which measure residence time distribution are good methods for establishing the efficiency of an installation. The Audubon Sugar Institute (Birket and Stein, 2004) has reported on tracer test carried out on three designs of vertical cooling crystalliser; supplied by Honiron, Silver and Fletcher Smith (now Fives Fletcher). These illustrate the contrasting results that can be obtained. In the case of the Honiron crystalliser which had a nominal retention time of 11 hour the tracer peak was obtained after 2 hours. The tracer peak in the Silver crystalliser, which had a nominal retention time of 17 hours, was obtained after 12 hours. Fletcher Smith crystalliser tracer peak, obtained after 38 hours, was closest to its nominal retention time, which was 42 hours.

6.2 Cooling water flow path

Achieving efficient counter-current flow, maintaining acceptable pressure drops and avoiding air locking problems are all important design considerations for a crystalliser cooling water circuit. As a result of its simplicity and low cost the temperature control method employed by most installations around the world comprises regulating the rate of water flow through the cooling circuit. However, this type of control only provides a limited degree of responsiveness and is not the most efficient option. A system now adopted by Fives Cail and Fives Fletcher is to supply a constant flow of water to the crystalliser and then to adjust the cooling regime of the crystalliser by adjusting the temperature of the cooling water being fed to the cooling crystalliser. It gives good results and can be achieved relatively simply and cheaply. It has the added advantage that constant fluid velocities are maintained in the cooling circuit, which aids heat transfer and minimises potential for problems of scaling and settling out of solids.

7 Conclusions

The requirements for good vertical cooling crystalliser design, as detailed by Love (2001) are:

- Controlled cooling (matching the cooling profile to the supersaturation and crystallisation characteristics).
- Uniform flow (i.e. an approach to plug flow, where all massecuite has the same retention time).
- Even temperature distribution transverse to the flow path (so that all massecuite experiences the intended cooling profile).
- No dead spots or short circuiting between the inlet and outlet (for full utilisation of installed volume).

In order to, as best as possible, achieve these aims it is important to properly evaluate and design the various features of a vertical crystalliser. This is of particular importance for massecuite cooling because there is a natural tendency for short-circuiting and dead area formation to occur during this process. A ‘efficient, robust and simple’ philosophy that has been adopted by Fives Cail and Fives Fletcher together with a considered approach to design decisions, using the principals explained, has produced an efficient and successful vertical cooling crystalliser design.

Acknowledgements

The author would like to acknowledge and thank John Elwall, whose notes and reports have been the major source for this work.

References


Développements récents dans la conception des cristallisoirs de refroidissement verticaux (R.sum.1)

Dans les installations modernes, les cristallisoirs de refroidissement verticaux sont actuellement préférés aux cristallisoirs horizontaux traditionnels cause des avantages significatifs qu’ils présentent, entre autres: des volumes plus grands pour une surface réduite au sol, ils conviennent mieux pour une installation extérieure, ils ont un meilleur rapport surface de refroidissement / volume et une meilleure aptitude à traiter des masses cuites de haute viscosité. Depuis l’introduction des premiers cristallisoirs de refroidissement verticaux il y a près de 40 ans, leur capacité a cru continuellement passant
d’une capacité initiale de 50 à 200 m³ à une capacité habituelle aujourd’hui de 300 à 400 m³ avec une tendance vers des unités encore plus grandes. Ces grands cristalliseurs présentent des exigences de construction importantes. Un bon cristalliseur vertical de refroidissement moderne exige une construction robuste de la surface thermoconductrice, du mélangeur et des dispositifs d’entraînement couplés ayant des qualités permettant un bon transfert calorifique et des conditions d’écoulement uniforme de la masse cuite. Cela exige une grande minutie dans la construction et la disposition des tubes de refroidissement et du mélangeur. L’utilisation d’engrenages planetaires modernes et de moteur de fréquence variable permet en plus d’augmenter la puissance et la fiabilité. Comment ces caractéristiques de construction sont-elles incluses dans une unité moderne ? En se référant comme exemple une masse cuite arrière produit de sucre de canne avec des installations de Fives-Cail et de Fives-Fletcher.

Desarrollos recientes en el diseño de cristalizadores-enfriadores verticales (Resumen)
En plantas nuevas se prefiere instalar cristalizadores-enfriadores verticales por la serie de ventajas que tienen frente a cristalizadores tradicionales horizontales, tales como mayor volumen en menor área, posible montaje al aire libre, mejor relación entre superficie de enfriamiento y volumen, mejor trabajo con magmas altamente viscosos etc. Desde la introducción de cristalizadores-enfriadores verticales hace casi 40 años, su volumen de trabajo ha aumentado constantemente desde primero 50-200 m³ hasta ahora los usuales 300-400 m³ con la tendencia a unidades aún más grandes. Cristalizadores grandes implican exigencias importantes de construcción: un cristalizador-enfriador vertical requiere tanto construcción robusta de los tubos de enfriamiento y del agitador como también una construcción robusta de la superficie de transferencia de calor, del agitador y de las unidades de accionamiento que permitan una buena transferencia de calor y un comportamiento continuo del flujo del magma. Con el empleo de engranajes planetarios modernos y de motores teledirigidos aún se pueden aumentar el rendimiento y la seguridad. Se describen estas propiedades de construcción en plantas de Fives-Cail y Fives-Fletcher, especialmente en lo que se refiere al magma de bajo grado de la producción de azúcar de cana.

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