RECENT DEVELOPMENTS IN VERTICAL CRYSTALLISER DESIGN

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Abstract

In modern installations vertical crystallisers are now preferred over traditional horizontal units because of the significant benefits they offer, which include larger volumes and smaller floor space, 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 crystallisers were introduced, nearly 40 years ago, there has been a steady increase in their unit size from initial volumes in the 50-200 m^3 range up to the present day where the most general unit size is now in the 300-400 m^3 range, with even larger units becoming increasingly common. Large crystallisers present some significant design challenges and a good modern vertical 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 Fletcher units as an example.

Keywords: crystalliser, vertical, cooling, stirrer, massecuite, viscosity.

Introduction

The additional massecuite exhaustion that can be achieved through cooling and mixing massecuite discharged from a vacuum pan in crystallisers is both significant and valuable. It is of particular importance for C-massecuites, in order to ensure that the lowest possible final 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 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 floor space 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 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 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 300-400 m³ range, with even larger units becoming increasingly common. A clear illustration of this point is given in Figure 1, which shows the unit size trends of vertical crystallisers (VCs) supplied by Fives Fletcher (FF) annually over the past 25 years.
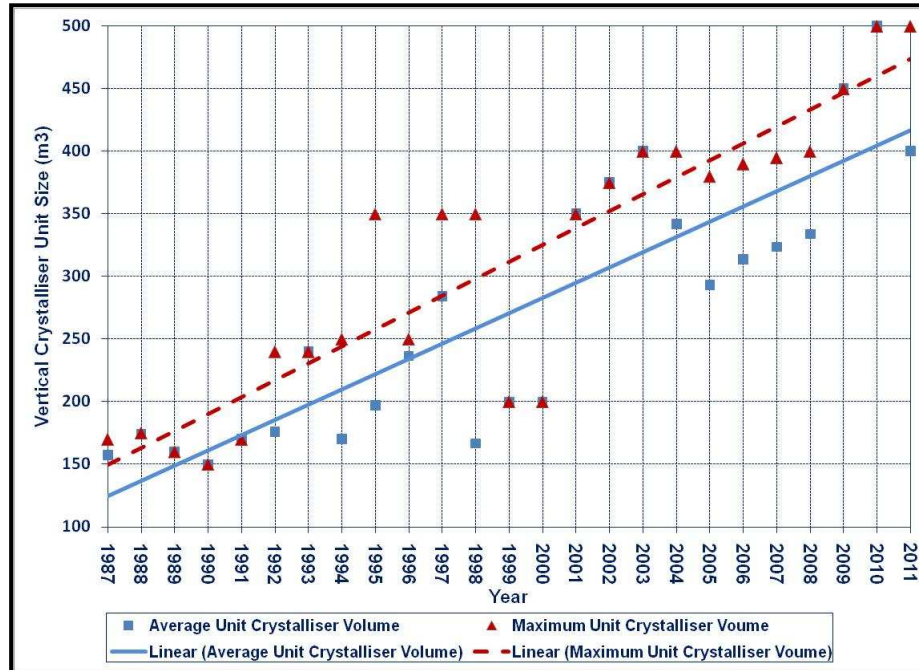

Figure 1. Volumetric unit size trends over the past 25 years of FF supplied VCs

A considerable number of different vertical 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 flow 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 brix or degree of cooling has to be restricted because of equipment limitations. This underlines the importance of having both well-designed and properly operated equipment and highlights the significant design challenges that large modern vertical crystallisers present.

Design aspects that have to be considered with vertical 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 crystallisers. The essential design approach adopted by FF for its vertical crystallisers (VC) has been to make them as efficient, robust and as simple as possible.

Design Considerations – Vessel Diameter and Height

Selecting the vessel diameter and height to be used for a vertical crystalliser requires evaluating the relative merits between a tall narrow vessel and a shorter squatter shape. The range of diameters for vertical crystallisers used by equipment suppliers varies from three to eight metres with heights ranging from eight to >30 metres. 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. The 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. The massecuite and water pumps will also have to deliver at higher pressures. On the other hand, large diameter VCs 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.

FF currently uses three standard VC diameters of 4.5, 5.25 and 5.75 m, with shell heights ranging from 12 to 24 m giving VCs with volumetric capacities ranging from 150 to 500 m^3. This gives aspect ratios ranging from 5.0 down to 2.5 as a minimum, which FF considers gives the best compromise between the conflicting 'narrow and thin' versus 'short and squat' shape requirements.

Design Considerations – Cooling Surface Configuration

Whilst some level of cooling in vertical 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 FF assumes 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.

Moving Versus Static Cooling Elements.
Vertical 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 numbers of different forms of rotating cooling elements have been tested these include discs or plates, finned 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 crack leaks 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.

Static cooling elements.
Mainly for the reasons mentioned above, fixed or static cooling surfaces are more commonly used in modern large VCs. The elements also come in a number of different forms (such as disks, plates, plain and finned 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. This 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. The smaller tube diameters can also result in much higher water pressure drops in large crystallisers operating with full counter current flow.

The tube banks can be arranged in a spiral formation 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 find 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 Figure 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.

Cooling Element Design for FF VCs.
In keeping with the philosophy of maintaining an efficient, simple and robust design FF employs static cooling elements comprising large diameter (consequently strong) tubes passing right through the shell. This means the shell provides support for the tubes and the tubes provide extra strength and rigidity to the shell. This also means all 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. The 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 tube 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

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ratios ranging from 1.0 to 2.0 m^{-1} can be obtained. Most other designs of VC with static cooling elements are restricted to a maximum value of around 1.6 m^{-1} for their S/V ratios.
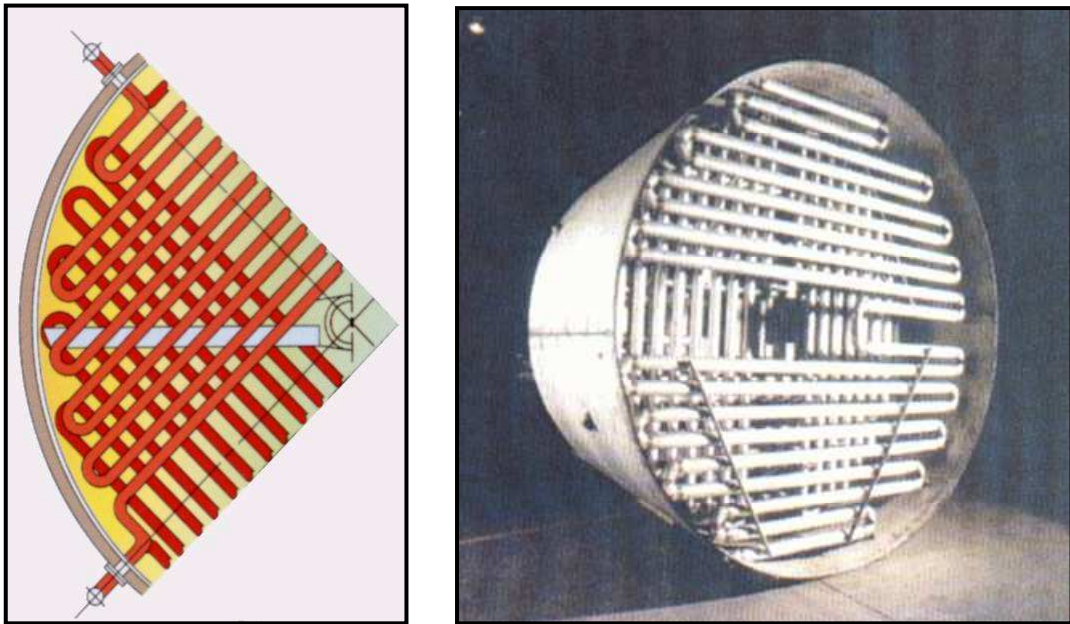

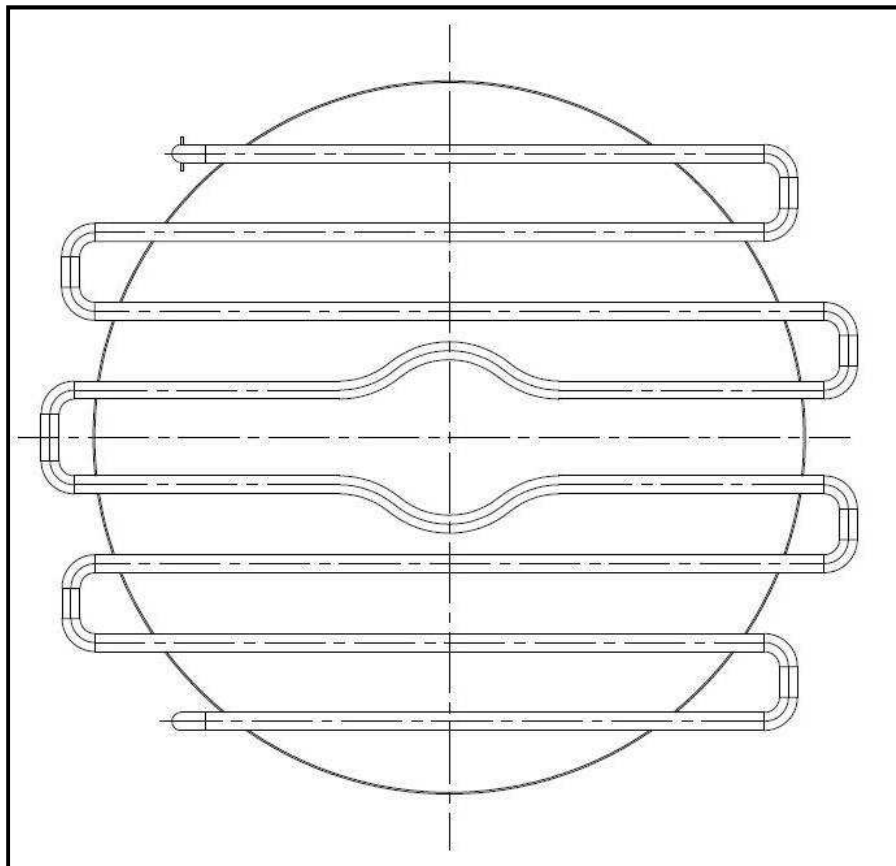**Figure 2. Static tube layout with alternate banks arranged at right angles to each other.**
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Figure 3. Fives Fletcher static tube layout.

Cooling Objectives and Constraints.

Cane C-massecuites are normally delivered to vertical crystallisers, from vacuum pans or strike receivers, at temperatures varying from 70 to 65°C. The 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 hours, following which there was a slower drop up to 45-48 hours and virtually no further purity drop after this. The standard residence time values used by Fives Fletcher for designing C-crystalliser installations are from 35 to 40 hours.

The range of heat transfer coefficients (HTC's) for cane C-massecuite cooling that is reported in published literature is large. The reason for which can be explained by the large effect the condition of the massecuite being processed exerts on the HTCs. With low brix, high temperature, low viscosity massecuites the HTCs can be orders of magnitude higher than those obtained with high brix, 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/(m^2.°C), with mean values ranging from 15 to 29 W/(m^2.°C). Of course cooling surface design and the amount of shear being achieved by the agitators are also important factors affecting HTC's. Fives Fletcher uses values ranging from 16 to 20 W/(m^2.°C) for general design purposes.

For typical design conditions (i.e. cooling in VCs from 70-65 °C down 45-40 °C with retention times of 35-40 hours) the average massecuite cooling rates will range from 0.5 to 0.9 °C/h. However, in many situations vertical crystallisers 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 that FF has recently designed for a cane C-massecuite vertical crystalliser installation is 1.3 °C/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 HTC's used by FF.

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 ⁰C/h). In vertical crystallisers with counter current cooling water circuits the high temperatures and low viscosity of the massecuite at, and soon after, entry means the HTCs 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.

Table 1
Vertical Crystallisers S/V Ratio and HTC Effecting on Massecuite Cooling Rates

Cooling water temperature into VC	32 ºC	Case 1			Case 2			Case 3		
Massecuite temperature into VC	ºC	65			70			70		
Massecuite temperature out of VC	ºC	45			40			55	53	50
Massecuite retention time in VC	h	40			35			12		
Massecuite cooling rate	ºC/h	0.5			0.9			1.3	1.4	1.7
Heat transfer coefficient	W/(m^2.ºC)	16	18	20	16	18	20	25		
Required S/V ratio	m^{-1}	0.9	0.8	0.6	1.7	1.5	1.3	1.2	1.4	1.6

Design Considerations – Agitator Configuration

Studies and CFD modelling (McBain et al, 2002) have shown that stirring in VCs is important for breaking up thermal wakes and creating a uniform temperature field between cooling tube banks. This creation of a uniform temperature field helps to avoiding heat transfer from being wasted on already cooled massecuite and to eliminate excessively hot or cold regions. This 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. The stirrer arms are mounted as close to the cooling surfaces as practical without making contact. The 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 Figure 4 which shows a stirrer and tube banks being fitted into a VC vessel).

Figure 4. A cooling element and stirrer assembly being fitted into a VC shell.

Keast and Sichter (1984) have reported on an evaluation that involved reducing the clearance between the stirrer arms and cooling elements from 10-15 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.

The other stirrer design concept is based on the use of the considerable drag developed by passing a solid object through a very viscous material to create a shearing action above and below the stirrer arms and the fixed cooling elements. This concept, used in Fives Fletcher VC stirrers, is the one demonstrated by McBain et al (2002) to break up the thermal wakes and achieve the re-establishment of uniform temperature fields. Illustrations of the stirrer design are shown in the Figures 5 and 6. This design is simple, robust and able to establish a good shearing action whilst not drawing too much power.
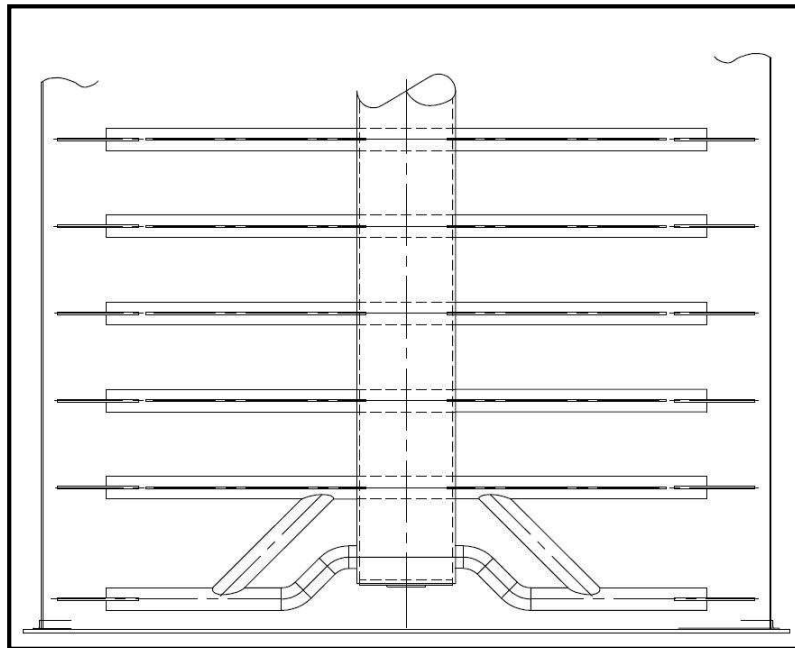

Figure 5. An FF crystalliser stirrer illustration.

Figure 6. A view of an FF stirrer inside a crystalliser.

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Design Considerations – Agitator Drives

A number of different vertical crystalliser stirrer drive designs exist, with the major division starting with whether they are hydraulic or electric powered.

Hydraulic Drives.
All hydraulic arrangements require a hydraulic pump pack and a hydraulic crystalliser 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 fiddly 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.

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 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 Fletcher has, 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 even entail specialist or manufacturer support if any fault develops. Therefore, in order to provide the highest degree of protection, FF uses a variable frequency drive (VFD) system with these reducers 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 FF has added further enhancements 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. brix, 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). FF has used the facilities of their latest planetary gear reducer, VFDs and associated control philosophy to maximise the shear through all the operating conditions. In order to achieve this FF has designed the system to have a capability to not only 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 revolutions per minute (rpm) up to 0.5 rpm. Figure 5 shows a control system screen for a VC using this control scheme.
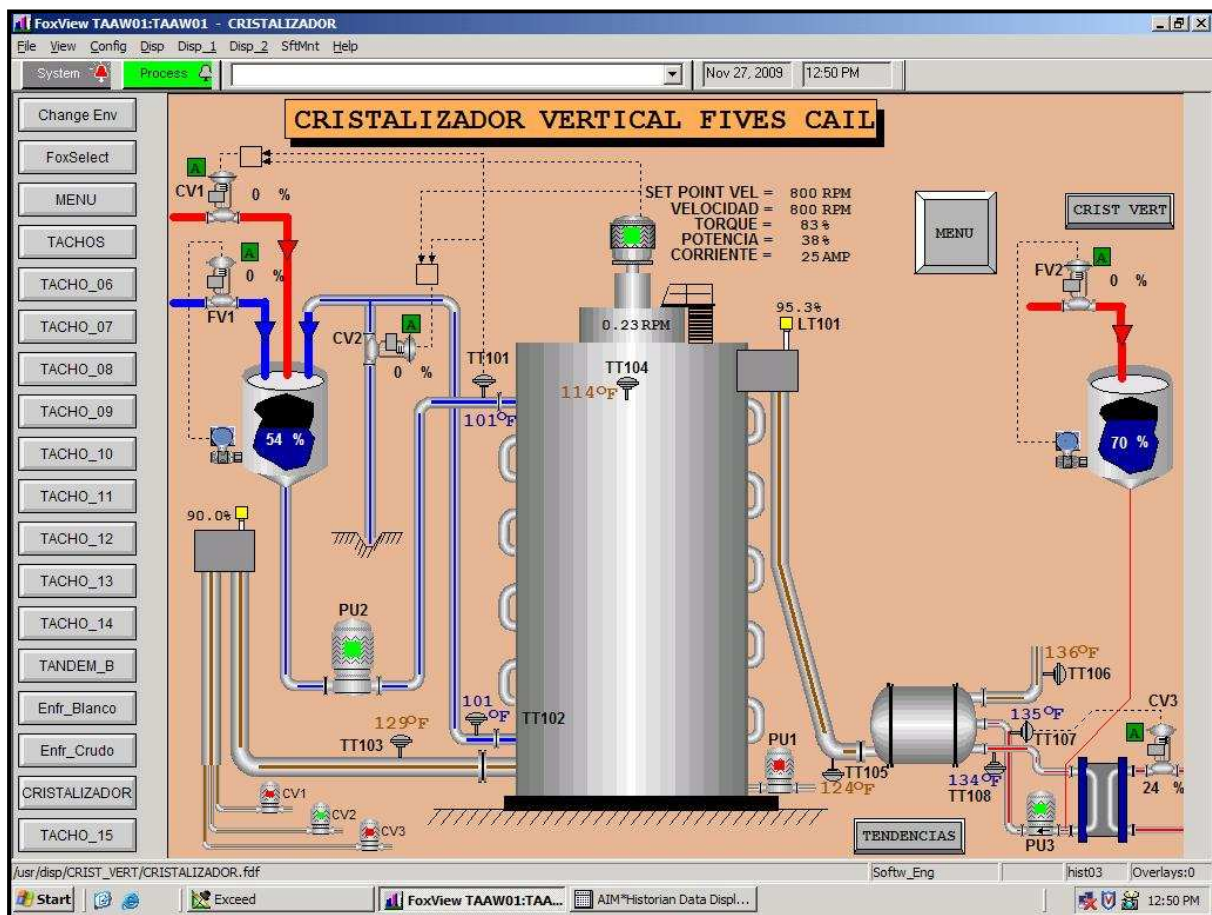

Figure 7. An FF vertical crystalliser control system mimic display.

Design Considerations – Flow Path

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. This is because on the one hand a

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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. The influence and interaction that a VC's 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. The use of baffles to help direct the flow and prevent preferential flow path and bypassing is the final feature that FF VCs 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 on three designs of vertical 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. The Fletcher Smith crystalliser tracer peak, obtained after 38 hours, was closest to its nominal retention time, which was 42 hours.

Cooling Water Flow Path
Achieving efficient count-current flow, maintaining acceptable pressure drops and avoiding air locking problems are all important design considerations for VC cooling water circuit. As a result of its simplicity and cheap cost the temperature control method employed by most VC 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. The system now adopted by FF 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 VC. This 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.

Conclusions

The requirements for good crystallisers 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 VC. 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. The 'efficient, robust and simple' philosophy that has been adopted by FF together with a considered approach to design decisions, using the principals explained, has produced an efficient and successful vertical crystalliser design.

Acknowledgements

References

Birkett H., and Stein J. (2004). Evaluation of C crystallizers and C massecuite reheaters. Proc American Soc. Sugar Cane Technol.

Hugot E. (1986). Handbook of cane sugar engineering. Elsevier Publishing.

Keast W.J. and Sichter N.J. (1984). Vertical continuous crystalliser – Victoria mill. Proc. Aust. Soc. Sugar Cane Technol., Vol 4: 293-299.

Love D.J. (2001). Design of continuous crystallisers to optimise flow patterns. Proc Int. Soc. Sugar Cane Technol., 24: 409-410.

McBain G.D., Harris J.A., Miller K.F. and Vigh S.N. (2002). Temperature distribution in a vertical cooling crystalliser. Proc. Aust. Soc. Sugar Cane Technol., Vol 24.

Rein P.W. (1980). A study of continuous low grade crystalliser performance. Proc Int. Soc. Sugar Cane Technol., 17: 2309-2327.

Rein P.W. (2007). Cane sugar engineering. Verlag Dr. Albert Bartens KG – Berlin.

Steindl R.H., Broadfoot R., and Miller K.F. (2001). Development and application of a model for low-grade cooling crystallisation. Proc Int. Soc. Sugar Cane Technol., 24: 116-123.

Van der Poel P.W., Schiweck H., Schwartz T. (1998). Sugar technology beet and cane sugar manufacture. Verlag Dr. Albert Bartens KG – Berlin.