THE SKIL/BOSCH CVP

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ABSTRACT

Despite their obvious benefits, commercially successful continuous vacuum pans [CVPs] were only introduced into the sugar industry during the 1970s. Since then they have been intensively studied and crystal uniformity, energy efficiency and pan availability have been identified as key performance criteria. This paper discusses these criteria and their application in the development of a new CVP.

Third party analyses of the performance of the new pans on both high and low grade massecuites are reported. The results show that the pans have met or exceeded all the objectives in regard to crystal quality, energy efficiency, operability and availability. The success is attributed to a sound design, drawing on the best characteristics of conventional CVPs with the addition of innovative features that enhance performance in critical areas such as crystal uniformity and heat transfer.

INTRODUCTION

The first proposal for a continuous vacuum pan was a 1931 patent by Werkspoor but it was another 30 years before the first acceptable [and hence commercially successful] CVP was produced by Fives Cail Babcock. That used a horizontal cylindrical body with vertical plate heating elements and subsequently evolved to horizontal tube heating. Much more successful was the horizontal Tongaat-Hulett CVP with vertical tubes and a ‘baby’s bottom’ cross section. That was the subject of a BSST paper a few years ago.

Last year we had another paper at the BSST AGM about the third main type of CVP: the BMA vertical arrangement with four or five pans stacked up in a tower [the VKT].

This paper describes a relatively new horizontal CVP, the thinking behind its development and the first detailed analysis of its performance. It was originally developed under the SKIL name but the license was subsequently sold to Bosch Projects.

DESIGN OBJECTIVES

The essential duty of any CVP is to accept the seed massecuite and the syrup, molasses and/or water fed to it and convert these to a well-exhausted strike massecuite with uniformly larger crystals and of higher brix. For this, an adequate heating surface for the evaporation duty and an adequate volume (retention time) for the crystal growth are required. However many other factors need to be correct to sustain efficient production of an acceptable quality massecuite. The most important are:

- crystal quality,
- energy efficiency and
- pan availability.

These and the related design decisions are discussed below.

Crystal Quality

This requirement is listed first, as it is the requirement that failed most of the early designs and remains a *sine qua non* for a successful design. The topic involves consideration of crystal uniformity, plug flow, compartment size, circulation and pan controls.

Crystal Uniformity

The most serious manifestation of uneven crystal size is false grain. In a batch pan this can be managed (at some cost) but CVP operations are not so tolerant, so the design must ensure that false grain is never initiated. However, a narrow size distribution of the "legitimate" crystal population is also a vital concern as this directly affects the permeability of massecuite in curing and any subsequent affination. Crystal size distribution is expressed as the coefficient of variation (CV).

Plug Flow

For a low CV, it is important that the crystals in the seed all remain in the CVP for the same length of time, something which is only possible with pure 'plug flow'.

Any continuous reactor can be mathematically modelled as an equivalent number of 'continuous stirred tank reactors' [CSTRs] in series: totally random flow results from a single such tank and perfect plug flow would require an infinite number of them.

Thelwall (2000) has used this approach to calculate expected final CV values (from good seed) against the number of theoretical tanks:

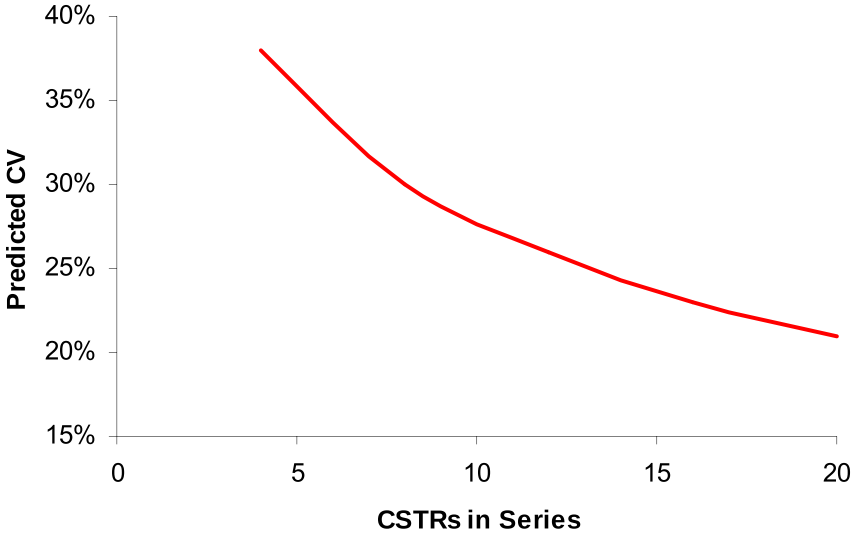

Figure 1: Predicted Crystal CV for Theoretical CSTRs

The reduction in incremental benefit as the number of tanks increases is clearly visible.

A good batch pan approximates to 12 CSTRs in series (Rein et al, 1985, and Broadfoot et al, 1989) and a practical target for continuous pan design is an equivalent of 12 to 16 CSTRs in series. CVPs are divided into compartments in order to assist with achieving plug flow but, as shown in Table 1 [over], the number of equivalent CSTRs does not necessarily equate to the number of actual compartments installed:

Table 1: Reported Equivalent CSTRs

Factory	Source	Make - Duty	Actual Cells	Equivalent CSTRs	Ratio
Maidstone	Rein *et al* (1985)	T-H - 'C'	12	23	1.9
Maidstone	Rein *et al* (1985)	T-H - 'A'	12	17	1.4
Maidstone	Rein *et al* (1985)	FCB - 'C'	15	9	0.6
Maryborough	Broadfoot *et al* (1989)	SRI - 'A'	9	12	1.3
Tully	Arcidiacono *et al*(1992)	X - 'B'	10	15	1.5
Racecourse	Attard (1993)	RCSA - 'C'	36	41	1.1

The good Tongaat-Hulett results can be explained by the smooth massecuite flow path without dead zones or short circuit paths. The Racecourse CVP demonstrated excellent plug flow characteristics because of its numerous baffles. However the baffles also caused circulation problems resulting in lump formation.

No equivalent test results for BMA VKTs were quoted in last year's BSST paper and none was found in the literature but it can be expected that the theoretical tanks would, by definition, approximate the number of real cells.

It should be noted that CV improves from seed to massecuite provided that the theoretical number of tanks is greater than 3 to 5, depending on seed CV: this was always achieved in the Tongaat-Hulett CVPs. Broadfoot (1992) has also pointed out that a CVP with a narrow residence time distribution can accept a seed of small size, thereby providing a high overall volumetric efficiency.

Given these advantages, it was an obvious decision that the new CVP should be of this genre. The pan has a smooth massecuite flow path and typically uses eight compartments, each with mid-compartment partial baffles. The partial baffles also serve as structural supports for the tube plate.

Compartment Size

Broadfoot and Allen (1977) showed by modelling that for CSTRs in series, the optimum CV will result from increasing cell sizes along the pan so as to provide equal crystal growth (approximately equal residence times) in each cell. This is the reason for the increasing cell sizes used by FCB and SRI.

However, if the flow *within* each cell approximates plug flow, there is no merit in varying the size of cells. The new pan aims for such plug flow within each cell and therefore uses equal cell sizes along the pan. Strong lateral circulation can be clearly seen in the pans, vindicating the equal cells decision.

Note that with equal cells, the greater crystal population per cell at the front end of the pan may require a higher feed rate to these cells but, if so, this is easily accommodated automatically by the feed controls.

Circulation: Natural and Induced

Rapid growth of crystals requires that they be continuously surrounded by a suitably supersaturated sucrose solution. For all crystals to grow at an even rate, they must all be equally exposed to this condition and for equal periods. Paradoxically, it is therefore vital that the circulation in an equal compartment CVP be constrained in order to approximate plug flow yet be sufficiently turbulent to mix and replenish the liquor films bounding the crystals.

The boiling process induces natural circulation. The vapour bubbles that form lower the effective density and cause a 'bubble lift'. Smooth-bored vertical tubes provide good heat transfer and offer the least hydraulic resistance [maximum bubble-lift] per unit of heating area. They are generally accepted as the most efficient for circulation.

For the upward circulation to be effective there must also be a sufficient unheated downcomer area for massecuite return. The ratio of flow area to wall surface in this area should be high. Long, narrow [high aspect ratio] vessels that are otherwise good for plug flow cannot meet this requirement and may suffer poor circulation.

Circulation on Maidstone's original FCB pan was poor until steam 'jiggers' were added (Graham and Radford, 1977). Circulation in the long-path, square-tubed Racecourse CVP "was improved considerably" when the hydraulic friction was reduced by the removal of 120 m^2 of baffles (Attard, 1993).

The best natural circulation appears to be achieved by long flow path, multi-cell, vertical tube pans so the new pan is of this type.

In some circumstances the natural circulation needs augmenting. The VKTs use mechanical stirrers to prevent conglomerates in high purity boilings. However, the simplest means to induce circulation is by steam jiggers (a supply of finely dispersed steam bubbles) beneath the calandria. These have been criticised as being wasteful of steam energy but this need not be so. The new pan, for instance, has been specifically designed to use calandria incondensables, supplemented by calandria vapour, for jigger purposes.

Pan controls

The near steady state of a CVP makes it simpler to control than a batch pan but accurate and reliable controls are essential because the consequences of any deviation – nucleation of new crystals or lumps from over-brixing for instance – are severe. It is critical that the condition of the massecuite be measured and controlled along the pan. Depending on the seed, the type of boiling and the size of the CVP, the most appropriate number of control points may be as few as 6 or as many as 12.

Love (2001) has shown that on/off feed control is technically superior to modulated control in this application. The accuracy of control attainable from an on-off system is shown by the trend plots in Figure 2 from the first pan shortly after commissioning. This system is used on all of the pans, with high grade pans controlled by RF and low grade usually controlled by lower cost conductivity sensors.

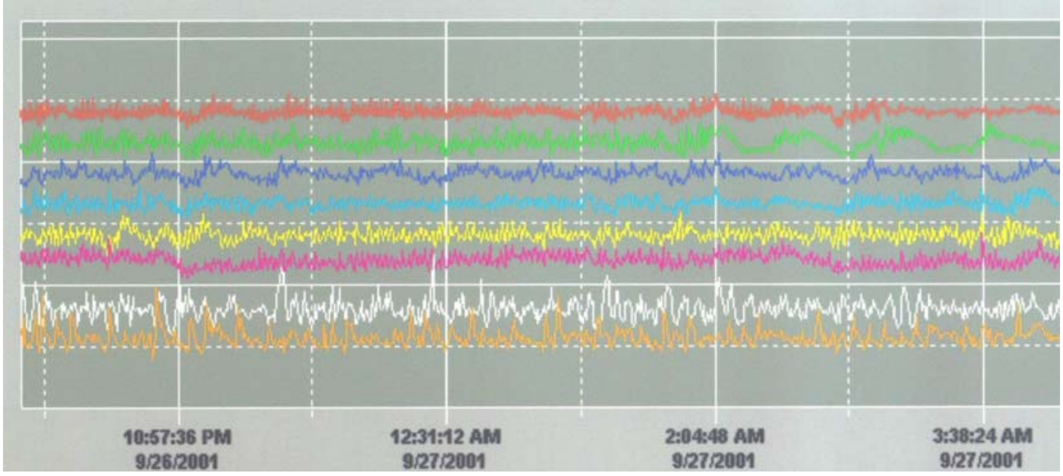

Figure 2: Conductivity Trends, Westfield 'C' pan

Steam and Energy Usage

Because of their low boiling heads and their higher heating surface / volume ratio during the final brixed-up stages of boiling, CVPs can usually operate on a lower grade of vapour than an equivalent batch pan. They are also more energy efficient because they take a steady steam flow and do not dissipate energy between boilings.

Many pans suffer from stagnant areas remote from the steam inlet where boiling is absent or less vigorous than elsewhere. These are usually due to the accumulation of incondensable gases, often because of poor steam passage design. More venting can sometimes restore boiling in such areas but this is obviously wasteful. It is better to ensure that steam velocities are maintained throughout the calandria.

Horizontal steam tubes are probably best in this regard but this compromises the massecuite flow path. The calandria of the new CVP uses simple internal baffles to ensure that steam velocities are maintained, even at the end remote from the steam supply. Numerous outlets are provided to drain the condensate into the special condensate chamber and, as has been mentioned already, incondensable gases are used as jigger – thereby eliminating energy loss from calandria venting. The pans can be seen to boil vigorously over the entire calandria surface.

Pan availability

In service, deposits on pan heating surfaces may reduce heat transfer and/or lumps may impede flow. The pan then has to be taken off line and boiled out on water. Pan availability is determined by the frequency and difficulty of these boil-outs.

Encrustation, build-ups and lump formation can all be serious problems in CVPs: encrustation is caused by massecuite splash adhering to surfaces above the massecuite level, build-ups occur below the massecuite surface and lumps occur when either of the above break loose. An acceptable pan design needs to inhibit all of these.

Encrustation

Any hot surfaces are potential encrustation zones and the propensity for encrustation is much greater with higher purities. Research and operating experience has shown that no surface finish, additive or material completely prevents encrustation but a liquor film will prevent it. Broadfoot *et al* (1989) showed that there was sufficient condensation on the cooler shell surfaces (even though lagged) to prevent encrustation.

The design of the new pan counters encrustation by:

- minimising internal surfaces in the most susceptible zone [the intermediate baffles extend only to surface level];
- providing cooling along the top of other internal partitions to create a condensation film;
- having no heated surfaces (e.g. steam pipes, incondensable vent lines or feed pipes) inside the pan above the massecuite level; and
- ensuring appropriate and sufficient feed controls and injection points in each compartment;

Build-ups

Build-ups arise mainly from a poor massecuite flow pattern, poor circulation or solidification on cool surfaces. In contrast to the situation above, cool surfaces within the massecuite raise viscosity and reduce or stop the flow.

Even in pans with good flow, build-ups often occur at the end of the downflow zone on the cool lower shell area beneath the calandria, particularly at reduced throughput rates. These are not easily dissolved by water boiling.

In addition to good flow, the design counters this problem by:

- distributing the hot feed liquor injection and some sight glass purging steam [incondensables] across the lowest surface of the shell;
- incorporating large transfer passages between compartments; and
- using the unique condensate collection chamber to provide a steam-heated wall under the massecuite beneath the calandria;

The condensate collection chamber can be seen in the cross-section of the new CVP [Figure 3]. This not only inhibits build-ups but also provides significant additional heating surface in the correct area to promote upward circulation into the calandria tubes.

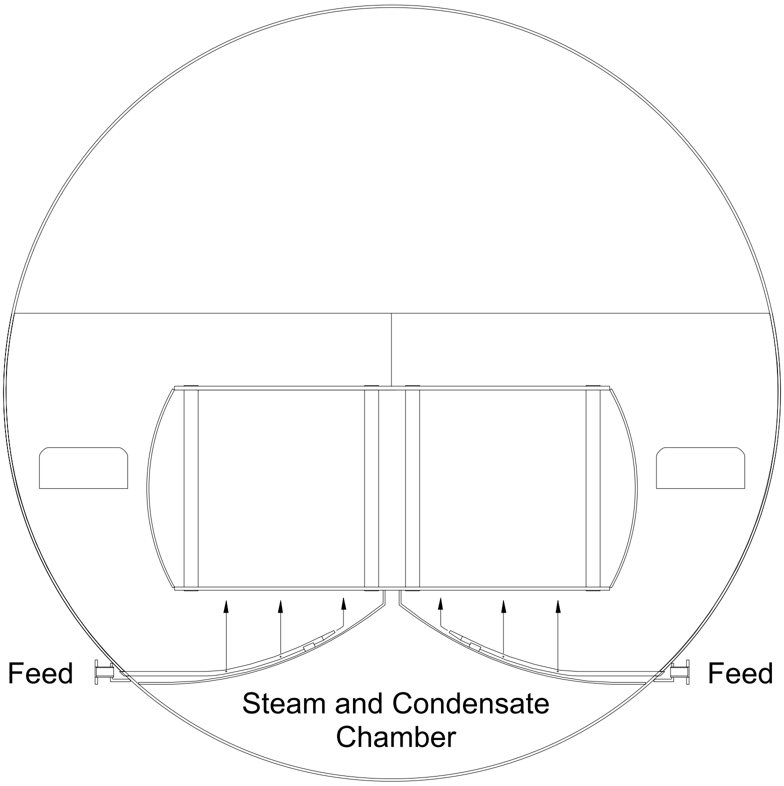

Figure 3: Steam-heated Surface beneath Calandria

Lumps

No lumps will occur if encrustation or build-ups are prevented. Encrustations usually break up quickly in turbulent zones and are easily dispersed in the massecuite but lumps from build-ups are more troublesome, so the prevention of sub-surface build-ups is particularly important.

RESULTING DESIGN

As discussed above, the most logical and successful genre of CVP is the horizontally arranged, long flow path, multi-cell type with vertical tubes. The design therefore followed this blueprint but added a number of innovations to enhance critical performance areas.

Unique features of the new CVP are:

- ***Built-in heating beneath calandria:*** the steam-heated condensate chamber provides additional heating to the massecuite beneath the calandria, promoting circulation and inhibiting build-up in this area. [The extra heated area is equal to approximately 5% of the tube surface].
- ***High heating surface, low steam pressure:*** the heating surface area / volume ratio [excluding the additional under-calandria heating area] in the standard designs is higher than offered by most competitors.
- ***Smooth massecuite flows:*** the new pan achieves a smooth-flow profile using constant radii for all curved surfaces.
- ***Mid-compartment baffles:*** mid-compartment partial baffles in the most active flow zones above and below the calandria, reinforce plug flow and effectively give the characteristics of additional cells, without impeding free circulation in the downcomers.
- ***Operator friendly:*** all valves and controls are easily accessed from control platform – none under the pan or above operator reach. Sight glasses are also at a convenient level and access for internal inspection is by a large, easily accessible, manway.
- ***Visible condensate flows:*** the condensate flows from multiple drains along the calandria which ensure free drainage; the flows can be clearly seen through sight glasses in the condensate chamber. This is a popular feature for operators.
- ***Baffled calandria steam passages:*** steam flows through the calandria are guided by baffles which ensure no dead zones and effective purging of incondensable gases.
- ***Unique feed distribution:*** the syrup / molasses feed is distributed over the entire area beneath the calandria, through nozzles that can be easily cleaned if necessary.
- ***No separate jiggers:*** the syrup / molasses feed arrangements are such that no independent jigger supplies are needed.

PERFORMANCE OF THE NEW CVPS

As is to be expected, the design concepts were refined as results were obtained from the first pans put into service.

Early experience

Four of the CVPs had been commissioned by the end of 2002 and all boiled vigorously, meeting the design evaporation criteria. However, it was noted that performance on two of the ‘C’ pans reduced after 3 to 5 weeks: boiling remained vigorous along the outer parts of the calandria but was “flat” towards the middle. When one pan was opened, it was found that some of the tubes along the centre of the pan had become partially or completely blocked with massecuite. This was of serious concern, as these pans had been expected to operate for longer periods between boil-outs.

The cause of the problem was identified as the single line molasses feed position: flash from the feed was inducing a strong up-flow immediately above the feed point, effectively cutting off the intended circulation pattern below the calandria and lifting most of the massecuite through the outer zone of the calandria. Above the calandria, the high level in this area impeded the outflow from the middle of the pan, resulting in fairly static massecuite settling and hardening in the middle tubes.

The problem was resolved by splitting the feed into two lines, with a small amount along the original position (to maintain movement in the trough) and the rest injected about half way across the calandria. Following this change, all of the original pans now operate well.

That original experience also prompted a detailed review of the entire pan design so that newer pans are significantly improved, while retaining the unique patented features: the profile has been smoothed so that no feed is now needed in the trough and a new well-distributed feed system has been designed. The jigger steam arrangements have also been changed. The two profiles are compared in Figure 4 :

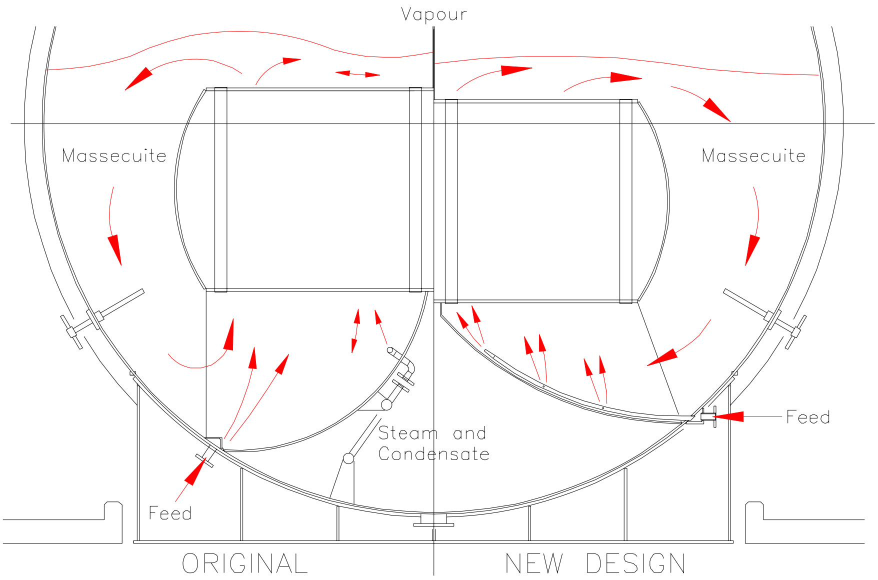

Figure 4: Comparison of Original and New Profiles

The new profile is remarkably similar to the ‘best’ profile derived from a recent computational fluid dynamics analysis of circulation patterns in continuous pans (Echeverri *et al.* 2005).

Performance tests

Two of the more recent pans, one an ‘A’ pan at Flacq United Estates [FUEL], Mauritius and the other a ‘C’ pan at Nghe An [NAT&L], Vietnam, have been subject to detailed independent analysis to measure their performance in the two critical parameters of crystal size distribution (CV) and heat transfer rate (HTC).

Residence Time Distribution

To evaluate the 8-compartment NAT&L pan, the South African Sugar Milling Research Institute [SMRI] was commissioned to specify crystal residence time test procedures. They designed the test and subsequently interpreted the results according to the procedures described by Rein et al (1985).

The atomic absorption spectrometer lithium analyses were performed by the quality assurance and testing center of the Vietnam Directorate for Standards and Quality. The test was conducted over 22 and 23 December 2006. Conditions were not ideal, being at a time of low and uneven throughput, but the results were nevertheless good.

Figure 5 shows the actual lithium tracer pattern compared to the best fit model, which was for 18 CSTRs:

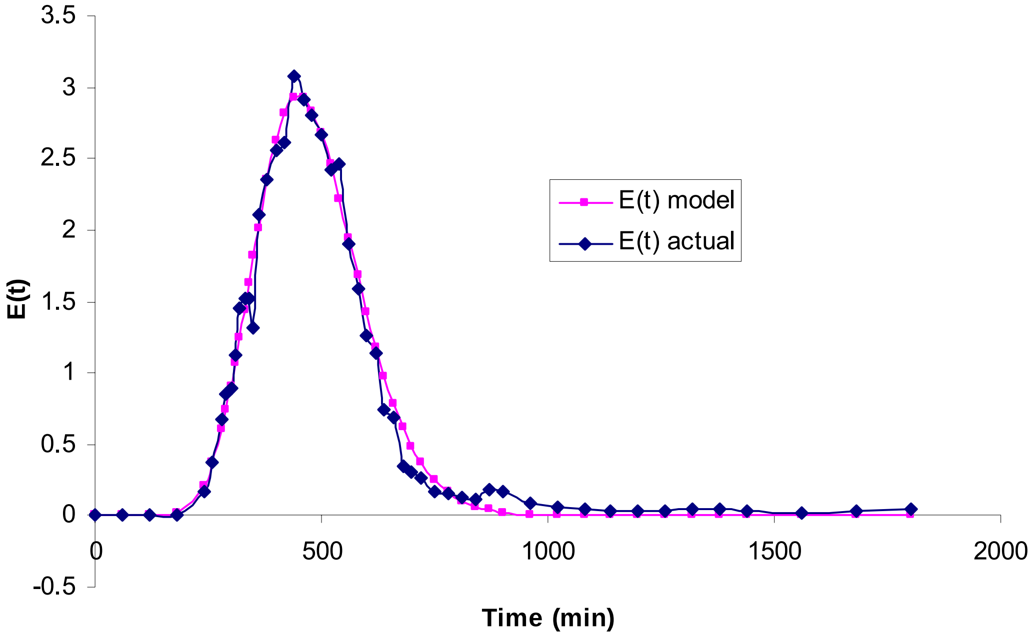

Figure 5 : Actual NAT&L tracer vs. 18 CSTR model

No tracer emerged in the first 3 hours, showing no short circuiting, and the low tail values indicated minimal hold-up areas. The high number of equivalent CSTRs confirms that the massecuite flows through the pan in a circulating spiral path with near to true plug flow.

The ratio of equivalent CSTRs to actual compartments is 2.3, better than any previously reported [see Table 1].

No lithium tracer testing was done at FUEL because of the special circumstances there. The pan was specified to handle all the 'A' massecuite after a future factory expansion but the expansion was deferred. In addition, the factory secured contracts to supply about 25% of its production as EEC special sugars which required the use of all the batch pans, including the one which had been intended for conditioning seed for the continuous pan.

Three of the 12 compartments in the CVP have therefore been temporarily isolated on the massecuite side and export quality sugar is produced directly from unconditioned magma produced in a screw conveyor beneath continuous B centrifugals. SMRI tests have shown that the high CV of the seed material is reduced by about 7 units through the pan's nine compartments.

Heat Transfer Coefficients and Steam Usage

The evaporation rate is an important CVP design parameter and is directly related to the overall heat transfer coefficient [HTC] achieved. The HTCs achieved at both FUEL and NAT&L were therefore measured.

HTCs in continuous pans can vary widely, depending mainly on massecuite purity and brix but other factors include the nature of the impurities, the ΔT between massecuite and steam, boiling temperature and tube cleanliness. These variables produce normal ranges of HTCs that cover the results measured from many pans.

The Audubon Sugar Institute recently reported average measurements from CVPs in Louisiana factories that fall neatly within these ranges (Anon, 2005, p.9). However, the HTCs measured on the new pans were at or significantly above the upper limit as shown in Table 2:

Table 2 : Comparison of Continuous Pan HTCs [kW/m²K]

	Normal Range		Louisiana	SKIL/Bosch
Massecuite	**Low**	**High**		
‘A’	0.2	0.44	0.32	0.54
‘B’	0.14	0.30	0.17	n/a
‘C’	0.11	0.22	0.16	0.22

The HTC is related to the ΔT between steam and massecuite: a certain ‘minimum’ ΔT being necessary to get any meaningful heat transfer through the overall resistance, after which the HTC is proportional to ΔT.

It is widely held by technologists that a minimum ΔT of about 25 K is necessary for satisfactory continuous pan boiling. Confirmation of the high HTC on the FUEL ‘A’ pan is that it was boiling vigorously and evaporating at 20.6 kg/m^2 with a ΔT of only 24.5 K when tested. This was four days after a boil-out and no jigger steam was being used.

The HTC of the NAT&L pan shown in Table 2 is the average of results measured on nine different daily runs in December 2006 and January 2007. This was a low throughput period during which the average steam temperature in the calandria was 96.9°C and average massecuite temperature 73.9°C, giving a ΔT of only 21 K. Jigger steam was used to maintain vigorous boiling under the exceptionally low ΔT.

Moor (2002) pointed out that CVP circulation can be boosted by using “free” incondensable gas jiggers in a suitably designed pan. Although jigger steam is not usually used on the FUEL. pan, this principle is used in providing purging steam to the feed sight glasses.

The high HTCs and low ΔTs on the pans enable the use of low grade vapours for boiling. The FUEL pan, for instance, boils on vacuum V3 at 93.5 K [80 kPa abs.], thereby maximising overall factory energy efficiency.

Encrustation and Build-up

‘A’ CVPs are most liable to encrustation. There are techniques to extend the cleaning intervals but they usually need to be boiled out weekly or two-weekly because of sugar settling in the base, lumps from encrustation in low-circulation tubes or build-up on surfaces above the massecuite. All of these have been countered in the new design: FUEL’s ‘A’ pan is routinely operated for 3 to 4 weeks between boil-outs. Boiling out is a short and simple operation.

Low grade CVPs can operate for longer periods between boil-outs. The pan at NAT&L is usually boiled out once or twice during the season with no special measures taken to reduce the build-up rate.

Exhaustion

In the end though, it is good exhaustion that is required of the pan, whether on ‘A’, ‘B’ or ‘C’ duty. Exhaustion data for the two test pans are presented in Table 3 [over] where

$$\textbf{\textit{Pan Exhaustion}} = \frac{10000 * \textbf{\textit{Drop}}}{\textbf{\textit{Massecuite}} * (100 - \textbf{\textit{Mother Liquor}})}$$

Table 3 : Exhaustion Data [%]

			Pol-Refractometer Purity①			Exhaustion
Factory	Duty	Period	Massecuite	Mother Liquor	Drop	
FUEL	‘A’	Test	87.20	68.80	18.4	67.6
		Crop 06	88.50	72.10	16.4	66.4
NAT&L	‘C’	Test	54.95	31.51	23.4	62.3
		March 07	58.50	32.76	25.7	65.4

① The NAT&L figures in Table 3 have been converted from original hydrometer (spindle) brix data using relationships established by MacGillivray and Graham (1969).

However, so many factors affect exhaustion – including feedstock quality and operating practices beyond the control of the design engineer – that comparisons must be treated with care, even when comparing one pan at different times of the crop period.

CONCLUSIONS

By drawing on the best features of established designs and adding innovative improvements, the new pan has been able to meet or exceed conventional performance standards for each of the key criteria of CVP design.

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