Experience with continuous crystallization of refined sugar at United Sugar Jeddah

A.S. Vawda*, A.E. Muneef and M. Voelling

United Sugar Company, Jeddah.

*Contact author: Email: avawda@savola.com

abstract

While most other unit operations have moved to continuous operation, refined sugar pan boiling is generally conducted in batch pans. The vertical continuous pan at United Sugar refinery in Jeddah has been successfully operating since 2007. It is possible to compare batch pan operation with continuous pan operation, as both systems operate in parallel. Generally speaking, the merits of a continuous process over a batch process are follows: Better plant utilization; higher operating and energy efficiency; and simpler process control. This paper examines the performance of the Jeddah continuous pan on the basis of: design features; heat and mass transfer; operating experience; crystal size distribution; sugar quality; fouling and encrustation; and instrumentation and control.

Keywords: **CDR Crystal Deposition Ratio, continuous pans, crystal size distribution, CV Coefficient of Variation, encrustation, HTC Heat Transfer Co-efficient, refined sugar, super saturation, VKT**

Experiencia con la cristalización continua de azúcar refinada en United Sugar, Jeddah

En tanto que la mayoría de las operaciones unitarias han pasado a una operación continua, la ebullición del azúcar en tachos sigue realizándose por tandas. La refinería de United Sugar en Jeddah ha estado operando exitosamente un tacho vertical continuo desde 2007. Es posible comparar la operación por tandas con la continua dado que ambos sistemas operan en paralelo. Las ventajas del proceso continuo sobre el proceso por tandas son, en general: mejor utilización de la planta, mayor eficiencia energética y de operación y un control de procesos más simple. Este trabajo examina el desempeño del proceso de tacho continuo en Jeddah sobre la base de: las características de diseño, las transferencias de masa y de calor, la experiencia de operación, la distribución de tamaños de los cristales, la calidad del azúcar, la suciedad y sarro, y la instrumentación y el control.

Experiência com contínua cristalização do açúcar refinado no United Sugar Jeddah

Enquanto a maioria das outras operações unitárias mudaram-se para operação contínua, a fervura do açúcar refinado é geralmente realizado em bandejas por lotes. A bandeja vertical contínua na refinaria United Sugar em Jeddah opera com sucesso desde 2007. É possível comparar operação em lotes com operação contínua, como ambos os sistemas funcionam em paralelo. De um modo geral, os méritos de um processo contínuo ao longo de um processo em lote são os seguintes: melhor utilização da planta; melhor funcionamento e a eficiência energética; e controle de processo mais simples. Este documento examina o desempenho da bandeja contínua de Jeddah com base no: 1) características de design; 2). calor e transferência de massa; 3) experiência de operação; 4) distribuição de tamanho de cristal; 5) qualidade do açúcar; 6) incrustação; e 7) instrumentação e controle.

Introduction

Over the last sixty years the sugar industry has gradually moved from batch to continuous processes. Raw sugar factories especially have adopted continuous boiling since the nineties and realised real benefits from these processes. However, concerns over perceived problems, mainly associated with low cycle times, have resulted in only a 30% application to A Massecuite boilings.[1]

In sugar refining, these same concerns have resulted in a reluctance to move to continuous white boiling. Some of the perceived reasons for the reluctance to adopt the continuous boiling process in refineries are as follows:

1. Low productivity
2. Poor coefficient of variation (CV)
3. Higher capital cost [2]

Despite the above, refinery continuous pans have made some inroads due to the application of technology applied to mitigate some of the disadvantages. United Sugar Company had planned a capacity expansion in 2005. It was decided to take advantage of this opportunity to expand and simultaneously improve the factory steam economy.

Reasons for selecting a continuous pan

The required expansion from 2500 tons per day (tpd) to 3000 tpd, with later 3500 and 4000 tpd, was approved in 2005. During the early stage of the design, the technical team conducted a survey of the capacity of the process units and identified deficiencies in various unit operations. It became obvious that increasing the refinery capacity using conventional technology would require the following additional equipment:

1. Steam generation
2. Desalination
3. Water demineralization
4. Batch pans
5. Strike receivers
6. Evaporators
7. Condensers

Being inside the port area, the refinery has very limited available space and the conventional design was not acceptable from both a cost and available space point of view.

After considering the need for improving energy efficiency and selecting equipment that was space friendly, a vertical continuous pan was considered to be the best solution (Figure 1).

The vertical continuous pan has the following advantages:

1. Being a weather-proof tower it could be located outside the building thereby realising savings in civil and steel structure. The 5.6m diameter requires a small pan foot print. Compare this to five batch pans located side by side.
2. Requiring low calandria pressure, it could operate on V1 vapour to improve over-all steam economy.
3. Producing refinery massecuite in a continuous pan would reduce the use of batch pans, thus minimising the cyclic pressure fluctuations in the exhaust steam range and the central vacuum system.
4. The attractiveness of adding a fifth cell in the future. This is more cost effective than installing an oversize pan. Over sizing has the disadvantage of wasted capital and the increased retention results in adverse quality of massecuite.
5. Having independent cells, means that different calandria pressures could be employed. In fact, the calandria steam can be sourced from different origins if necessary.

By far the most attractive argument in favour of the VKT was the lower over-all capital and operational cost. The batch pan system, with its buildings, batch pans and crystallizers cost 37% more. This does not take into account the additional equipment required for steam generation and condensing.

Design features

The vertical continuous pan (VKT) can simply be described as a number of batch pans stacked one on top of each other (Table 1). The pan boiling process is carried out by continuously feeding the seed crystals and sugar syrup to the unit, while withdrawing the final massecuite from the last chamber.

Figure 1. The 31 m tall VKT with the wash water tank in the foreground

The pan shell is 5.6m in diameter constructed of carbon steel. The massecuite contact area is SS304 clad up to 1000mm above the calandria. Each of the four chambers are similar to ordinary batch pans (Table 2).

Incondensable gasses are extracted as in normal batch pans.

Table 1. Comparison of a VKT cell and a batch pan at USC

	Batch pan	VKT
Pan diameter m	4.72	5.60
Down take diameter m	1.78	2.40
Diameter ratio	0.38	0.43
Tube diameter mm	101.60	101.60
Distance between tube plates m	0.95	1.30
Massecuite height above calandria m	2.25	0.40
Heating surface area m^2	353.00	636.00
Heating surface to volume ratio	5.90	12.00

Table 2. Specification of the VKT

Number of compartments	4
Massecuite volume per compartment	$50m^3$
Product retention time, at full capacity	2.1hr
Diameter of pan	5.6m
Heating surface of each chamber	$636m^2$
Overall cylinder height	31m

Figure 2. The three bladed impeller found in chambers 1 and 2

In this installation the incondensable gasses are vented to the vacuum main because the V1 vapour used for heating is sub atmospheric.

The entrainment prevention system consists of a vapour box containing baffles which change the direction of vapour, collecting droplets on impact.

Each compartment is provided with an agitator, the first two compartments with three bladed impellers and the last two with five bladed propeller stirrers (Figures 2 and 3). The first two are driven by a 37kW motor, while the last two compartments are served by 90kW motors. Final brix control in chamber 4 is provided by amps draw-off of the stirrer motor. Chamber 3 also has a 90kW motor in the event that compartment is off line for cleaning.

Table 3. Comparative heat and mass transfer performance data

	Continuous pan	USC batch pan
Evaporation rate kg/m²/h	13	35
Crystal deposition rate kg/m³/h	320	375
OHTC W/m²/C	470	680
Temperature difference calandria-vapour	31	58

Heat and mass transfer

The function of a pan is to transform sucrose from a liquid phase to a solid phase. This is accomplished in batch and continuous pans by maintaining a super saturation driving force by evaporation. The application of heat in continuous pans is comparatively gentle compared to that in batch pans.

Typical evaporation rate and crystal deposition rates are shown in Table 3.

Heat transfer

Modern vacuum pans have evolved over the years and today most pans, both batch and continuous, have vertical tubes and agitators.

The relationship between massecuite height and temperature difference between heating steam and vapour is shown by Austmeyer[3] in Figure 4.

It shows that with a low massecuite height, good HTC is achieved. It also shows that this can be achieved with a low temperature difference (deltaT) between calandria heating steam and massecuite.

The lower deltaT for the continuous pan compared to the batch pans, permits the use of bled vapour and the ensuing energy savings that comes with it. However, this lower deltaT comes at a price, in that the evaporation rate is lower per unit area compared to that in batch pans (Table 4).

Figure 3. The five bladed impeller found in chambers 3 and 4

Figure 4. Graph showing the influence of massecuite height on OHTC

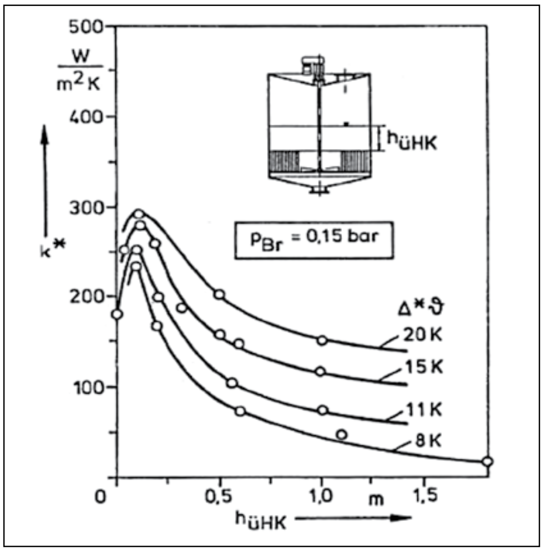


Table 4. Typical calandria steam pressures

	Units	Batch pan	Batch pan	Batch pan	Batch pan	CVP
		HR	USC	T+L	USCE	VKT
Calandria pressure	Bara	5.00	2.20	1.90	1.50	0.80
Vapour pressure	Bara	0.25	0.25	0.23	0.23	0.25
Boiling cycle time	Hrs	1.50	2.00	2.00	2.00	Cont.
Calandria type		Ribbon	Tubular	Tubular	Tubular	Tubular
Gross dT	°C	85	58	56	48	29

Table 5. Productivity comparison batch pan vs continuous pan

	Unit	Batch pan	Continuous pan
Total pan volume	m^3	240	260
Total massecuite output	MT/h	180	190
Massecuite output/volume	MT/m^3	0.75	0.73

Table 6. Progressive crystal growth and retention time

	MA mm	Retention time minutes	Massecuite flow t/h
Seed pan	0.43		
Cell 1	0.47	47	66
Cell 2	0.54	34	88
Cell 3	0.62	27	109
Cell 4	0.68	22	130
		130	

Table 7. Design performance vs actual

	Parameter	BMA	USC
Massecuite			
Mass flow rate	t/h	190.00	191.00
Brix	%	90.50	89.70
Mean crystal size	mm	0.60	0.68
Seed magma			
Mass flow rate	t/h	51.60	65.00
Dry matter	%	89.00	88.00
Mean crystal size	mm	0.38	0.43
Feed solution			
Mass flow rate	t/h	172.70	153.00
Purity	%	99.00	99.00
Brix	%	73.00	72.00
Heating steam pressure	bar(a)	0.70	0.75
Vapour pressure	bar(a)	0.20	0.25
Water evaporation	t/h	34.30	32.00
Seed to massecuite	%	27.10	34.50

The VKT and batch pans at USC have an average evaporation rate of 12 kg/m^2 and 40 kg/m^2, respectively. Continuous pans in general have more surface area which compensates for this evaporation difference. The heating surface to volume ratio for both types of pan is shown in Table 1.

Mass transfer

Refinery batch pans are fast crystallizing units because of the high purity product being boiled. The rate limiting factor is often said to be the evaporation rate which is much higher in batch pans than in continuous pans. The situation at USC is as follows:

Four 60m^3 batch pans (240m^3) produce a total of 180 MT massecuite per hour.

One VKT pan with a volume of 200m^3 produces 190 MT massecuite per hour.

The seed pan volume (60m^3) must also be included to the VKT volume. Table 5 shows that the difference between batch pans and continuous pans is negligible for high purity refinery boiling.

Since the centrifugal yield is higher in the continuous pan compared to the batch pan, this small difference is of no consequence.

Figure 5. Comparison of slurry showing poor quality on the left

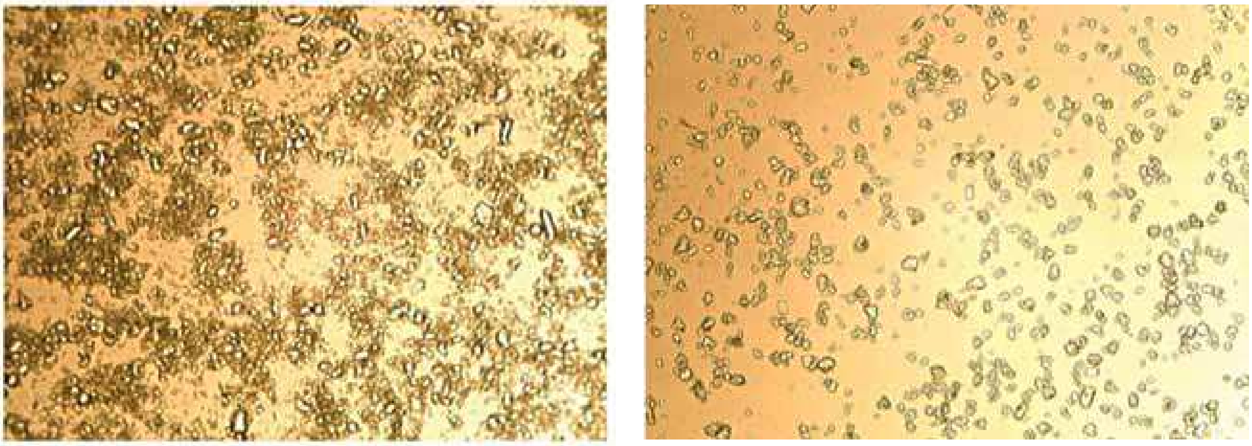


Table 8. Typical comparative crystal size analysis

	Continuous pan	Batch pan
Mean aperture	0.65 - 0.70	0.52 - 0.60
Coefficient of variation	32.40	35.60
Sugar less than 250 microns	2.20	9.50

Retention time

The retention time of the volume flow in a stirred tank reactor can be calculated from the tank volume and the mass flows.

During recent measurements, the average crystal growth rate in the VKT was 125 microns per hour - starting at 0.43mm seed crystal size and full growth at 0.68 mm (Tables 6 and 7).

The total retention time of the VKT is 2.1 hrs for the above case.

Operating experience

The first few weeks of operations were very difficult from an operational point of view. Despite the initial satisfactory performance under vendor training and supervision, the operation gradually deteriorated.

The VKT was started with four cells in operation. The level control of cell 3 malfunctioned and was taken off-line and the pan operated on three chambers only.

The quality of the massecuite was extremely poor with wide crystal size distribution and a poor CV. This phenomenon was worse in the coarse crystal range with a large percentage of crystals retained on the 2000 micron sieve deck.

Samples taken from the VKT revealed excessive agglomerates and oversized crystals. Samples taken before the seed massecuite pumps revealed similar poor crystal size distribution. This was positive news because it confirmed that the VKT was not the cause of the agglomerates and oversized crystals. Attention was then paid to the seed preparation which is key for good massecuite crystal size variation.[4]

Changes on parameters of the seed pan were carried out - constant vacuum, reduction of heating steam during seeding and minimizing the retention time at the slurry funnel - resulting in an improved crystal size distribution. However this still did not meet the USC specification.

Additional sampling carried out on slurry - diluted with fine liquor and microscopically analyzed - resulted in a similar crystal spectrum as found in chamber 4 massecuite, confirming that poor slurry was one of the major causes of the poor CV.

Other problems were also encountered:

1. The pan operators were finding it difficult to achieve the seed massecuite crystal size of 0.3 - 0.4 mm, producing 0.6 - 0.7 mm. The seed pan boiling program was changed from a step to a linear curve.

2. The slurry mill was producing poor quality slurry as seen under a microscope (Figure 5). This was due to worn ball-bearings.

3. The seed to massecuite ratio was often compromised due to seed shortage as the pan boilers were getting used to the new equipment. By reducing the output of the pan, the retention time and consequent crystal size increased.

4. The evaporation rate began declining after 7 days of operation as the encrustation increased resulting in large crystals and conglomerates.

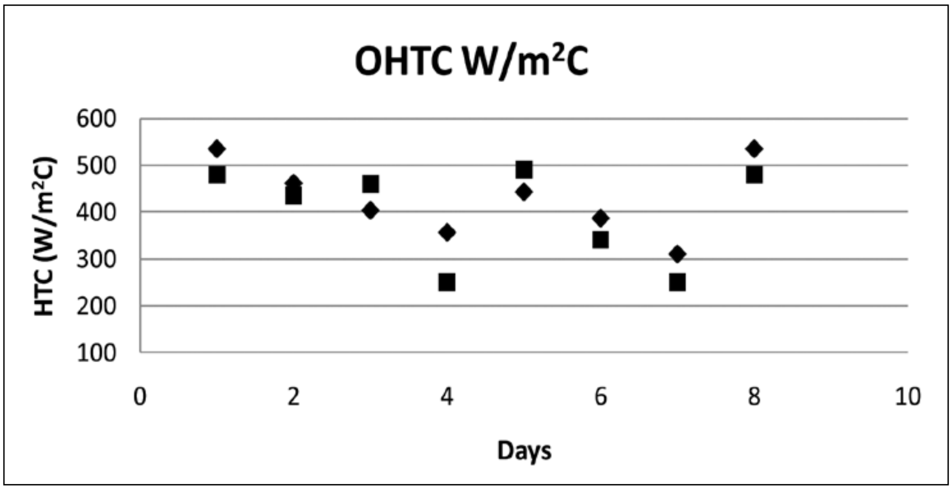
Systematic corrective actions taken to improve the seed quality and quantity, resulted in an improved operation. Seed pan control parameters were changed by opting for constant vacuum, reduction of calandria steam pressure during seeding and minimizing the retention time at the slurry funnel. The worn ball-bearings in the slurry mill were replaced.

A second seed pan was made available to ensure a minimum seed to massecuite ratio of 25%. A new proactive approach was taken with regards to boil outs. (This is discussed under the section on fouling and encrustation.)

There were several noticeable changes in the behaviour of the refinery when the VKT was operating properly:

1. Steadier pressure on the exhaust steam range due to steadier consumption of steam compared to batch pans. The other contributor to this steadiness was the new large first effect evaporator which delivers the required V1 vapour.

Figure 8. Drop in OHTC due to pan fouling



2. Steadier vacuum on the central vacuum system, due to a steady vapour generation from the VKT. Reduced vapour due to larger double effect evaporator configuration was also a factor. Simple and steady operations compared to the cyclical activity of batch pans.

3. Better massecuite quality which manifested itself by better purging with less wash water required.

Crystal size distribution

The quality of slurry, seed and the steady controlled conditions of the VKT and supporting systems has delivered a crystal quality which is satisfactory to USC and its customers. The quantity of false grain generated by the continuous pans is negligible compared to that produced by batch pans (Table 8).

The curve of the crystal size shape between the VKT and batch pans is distinctly different. The VKT produces consistently larger crystals and fewer smaller crystals.

The larger crystal size has a positive influence on the purging properties of the massecuite. The larger crystals offer larger interstitial spaces between crystals, allowing mother liquor free passage during centrifugation. The separation is easier.[5]

A sugar with larger crystals has a lower specific surface area (m^2/kg).[6] This smaller unit surface area makes the sugar easier to wash, so less water is required.

The crystal size distribution influences the purging properties of the massecuites because the crystals with a wide range of sizes, i.e. poor CV, will pack closely together during centrifugation and will hinder the free flow of mother liquor and wash water out of the basket.[8]

The VKT sugar crystal size variation is steady, while in the batch pan, every pan exhibits some variation in crystal size distribution and massecuite rheological behaviour, due to variation in brix and crystal content (Figures 6 and 7).

Sugar quality

In general, the sugar quality from the VKT was superior to the batch pan sugar, for all measured criteria.

Colour: Sugar colour from the VKT is better than from the batch pan at by about 15%. This is due to the higher MA and the lack of fines allowing for cleaner drainage of the mother liquor. Typically, with a fine liquor of colour 95 ICU, the wet sugar colour of VKT

Figure 6. Shape of crystal size in batch pans

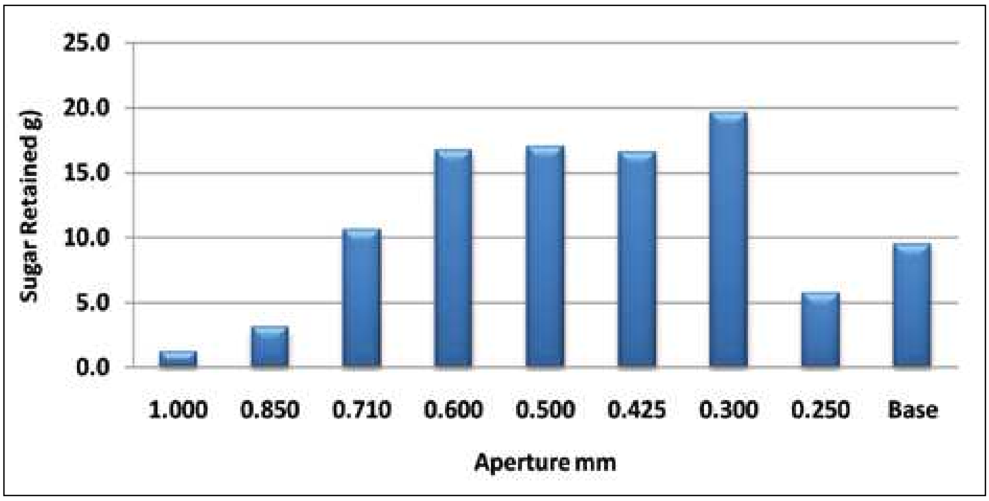


Figure 7. Shape of crystal size in continuous vacuum pan

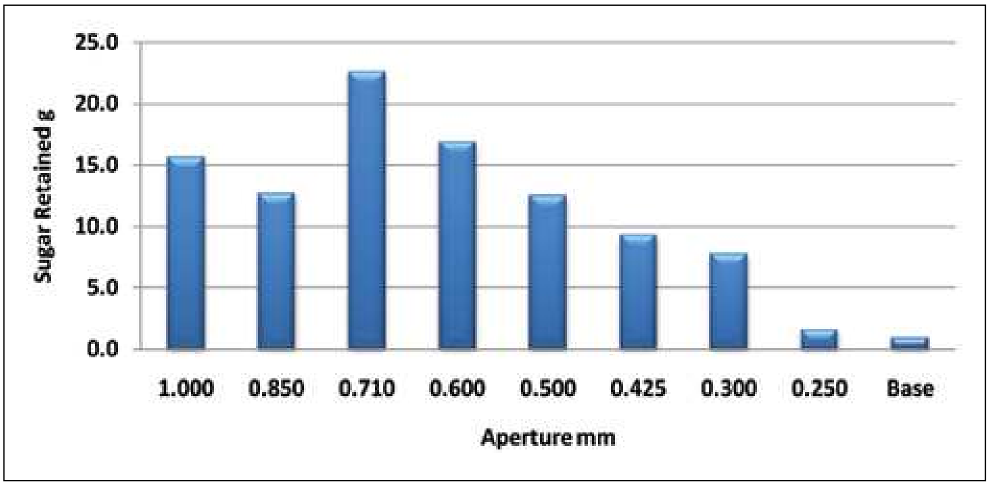


Figure 9. The thin stainless steel cladding

Figure 10. The liquor ring feed

and batch pan is about 6 ICU and 9 ICU, respectively - both using two seconds of wash water. The drying process increases the colour by 8 - 10 ICU.

Moisture: Centrifugal separation of the VKT massecuite is always cleaner and drier. The larger MA and comparative lack of tiny crystals ensured a drier final product.

Crystal size distribution: The VKT produces larger crystal size and less small crystal. The batch pan does the opposite. The slow evaporation rate and stable super saturation conditions ensure that the VKT produces less false grain.

Fouling and encrustation

In batch pans, steaming of the unit after every strike ensures that there is no residual sugar remaining on the walls, tubes etc. Continuous pans operate for long periods and are not subject to periodic discharge and steaming. Therefore encrustation in continuous pans is far more serious. Sucrose has a propensity to crystallize at high purity.[7]

The problem is a self-propagating chain reaction, where early encrustation causes a reduction of free circulation, leading to high pockets of supersaturated zones, resulting in the encrustation getting worse (Figure 8).

There are two well-known signs of the onset of encrustation in the USC vertical continuous pan. Firstly, there is a drop off in the evaporation rate and secondly, a deterioration of the cv, notably the appearance of a large crop of crystals above 2 mm in size.

Encrustation above the boiling surface is low because of the following reasons:

a. There are no sharp corners or edges for encrustation to take hold. The calandria is equipped with flush welded heating tubes resulting in a seamless flat tube plate.

b. Splashing is minimal due to the gentle boiling action as a result of the low temperature difference between heating steam and massecuite. The evaporation rate seldom exceeds 13 kg/m^{2}C compared with the batch pan where 60 kg/m^{2}C is quite common.

c. The syrup feed is administered above the massecuite on the inside walls of the pan using a ring distributor. The discharge holes on this ring faces the pan wall and feed runs down the wall keeping it wet and washed. This method of applying the feed washes down any potential wall based encrustation.

d. The stainless steel cladding is a thin plate welded at the edges. This lining is able to flex and vibrate and encrustations do not appear to stick to it.

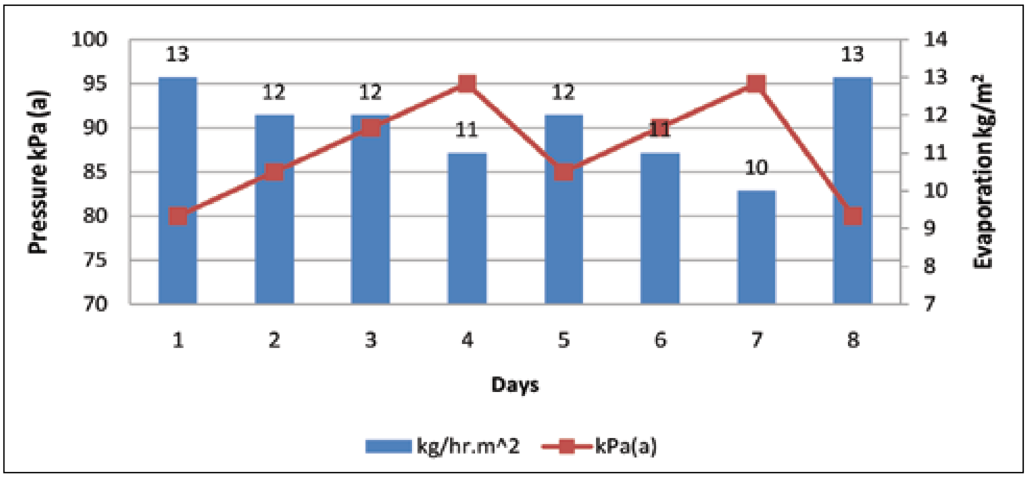
e. Constant and steady calandria pressure.

Encrustation rates are higher in the last compartment where the brix is slightly higher and the crystal content is at its highest. The last chamber is boiled out twice a week to manage this phenomenon.

It is normal for continuous pans processing A massecuite at 85 - 90 purity to operate for 2 - 3 weeks, however at USC the VKT boiling at 99% purity, seven days is the norm.

The stainless steel cladding is a thin plate welded

Figure 11. The relationship between calandria pressure and evaporation rate showing the pressure adjusted to maintain the evaporation rate and the recovery after a boil-out



at the edges (Figure 9). This lining is able to flex and vibrate and encrustations do not appear to stick to it.

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The proven standard operating procedure at USC is that all chambers are boiled out weekly, while chamber four is boiled once additionally during the middle of the same week. Before any cell is bypassed for water boiling, the other cells are ramped up by increasing calandria pressure and increasing the pan output so that there is no major production loss during the two hours the chamber is off line.

The vertical continuous pan design with multiple pans stacked in series, allows each chamber to be taken off line for water boiling. In order to reduce down time, hot water is first collected in a dedicated 60 m^3 tank which is served with a pump capable of delivering 80 m^3/h water. When a chamber is free of massecuite and ready for cleaning, water is pumped into it quickly within 15 minutes. After boiling for 60 minutes, the chamber is clean and the water is dropped back into the same tank. The contents of this tank are then slowly transferred to the sweet water. The outage time for any chamber on water boiling does not exceed 2.5 hours.

Instrumentation and control

The instrumentation found in continuous pans is very similar to that found in batch pans with some notable exceptions which will be discussed in this chapter.

There is however, one interesting difference between the vertical continuous pan, like the VKT, and a horizontal continuous pan like a THS CVP or FCB CVP. In a vertical pan the word 'compartment' has a different meaning. In horizontal CVPs, a compartment refers to a division in the massecuite holding chamber, while in a vertical pan a compartment is a totally isolated chamber which has its own calandria and vapour space.

The throughput of the pan is controlled by the calandria pressure of each chamber. The liquor feed flow depends on the evaporation rate (Figure 11). Consequently, the main control strategy involves the maintenance of a fixed ratio between seed and liquor feed. This means that the amount of sugar solids fed via syrup stays at the same ratio at any throughput capacity of the pan. The throughput capacity of the pan is controlled by the required evaporation rate which is controlled by calandria pressure control. Each cell can have a pre-set ratio so ramping the main pressure accelerator will not interfere in the ratio of calandria set for individual cells.

The absolute pressure of each compartment is controlled by a pressure transmitter and a 700 mm butterfly valve isolating the pan vapour space from the central vacuum header.

Brix control is provided by microwave probes which are provided with rinsing nozzles. These are timed to a pre-set interval of 7000 sec. and duration of wash water application of 8 sec. to remove encrustations. In batch pans these probes are cleaned between cycles when the batch pans receive a steam out. In the continuous pans there are no steam outs and the pan is expected to operate for many days between cleaning cycles.

Level control is provided by membrane type differential pressure transmitters which are also provided with suitable rinsing nozzles. A baffle plate installed in front of the level transmitter creates turbulence to rinse and remove encrustations within a pre-set time, without affecting the brix of the chamber.

Massecuite temperature is measured by PT100 temperature transmitters. Magnetic flow meters are employed for measuring condensate and feed liquor. The ratio of seed massecuite flow is controlled by inference using the shaft rotational speed in real time using VSD (Variable Speed Drive) At USC a vendor supplied a pan boiling program with the name "NAMAT" which has been implemented. This program controls the washing cycles, boiling pan, cleaning of chambers, seed and feed ratio semi automatically.

Conclusion

For refineries that require a moderate crystal size between 0.6 - 0.8mm or even bigger, the VKT has proven to be successful. The crystal size distribution is below 40 and when controlled properly can deliver a CV of 35.

The high purity issue of encrustation does not affect the capacity of the refinery due to the ability to bypass any of the four chambers for the short cleaning period.

The ability of the VKT to operate with a delta T of 30 degree Celsius allows the use of bled vapour, thus improving the over-all steam economy of the refinery.

The crystal deposition rate is slightly lower than the purchase specification and therefore the need for a slightly higher seed to massecuite ratio to deliver at full capacity.

Acknowledgement

The authors would like to acknowledge the support of the management of United Sugar for presenting this paper. Thanks also are due to Mr Eyad Nour for collecting some of the operational data and to Mr Faisal Wagdani for the numerous laboratory analyses.

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