ROBUST DESIGN OF AN EVAPORATOR STATION AS APPLIED TO THE XINAVANE REHABILITATION PROJECT

DJ LOVE[1], DM MEADOWS[2] AND RG HOEKSTRA[2]

[1]David Love Process Engineering cc, 45 Kelvin Place, Durban, 4051, South Africa
[2]Tongaat-Hulett Sugar Ltd., Private Bag 3, Glenashley, 4022, South Africa

Abstract

The rehabilitation of the Xinavane sugar factory in Mozambique necessitated a redesign of the evaporator station. The particular arrangement at Xinavane proved to be extremely sensitive to changes in operating parameters. Using this evaporator station as an example, the concept of design robustness (suitability under a range of operating conditions) is introduced. A rigorous evaporator simulation program was used to optimise heating surface and temperature driving force distribution along the evaporator train, and to model and minimise the potentially considerable effect on evaporator performance of variations in bleed rate. The unique requirements of evaporator station design are discussed, and some of the details of the equipment designed for Xinavane are presented.

Introduction

Recent design work for refurbishment of the Xinavane factory required the redesign of the evaporator station. Preliminary calculations highlighted the fact that some options for modifications would meet the new requirements for the selected design parameters, but the performance would deteriorate rapidly if the design parameters were slightly different. This highlighted the need for a robust evaporator design which was not as sensitive to design parameters.

Refurbishment of the Xinavane factory

Xinavane sugar mill (known previously as Inkomati mill) is located in southern Mozambique some 110 km from Maputo. In 1998 Tongaat-Hulett Sugar purchased a share in the mill, with the remaining share being held by the Mozambican government. At its previous production peak, in the 1971 season, the mill crushed 483 147 tons of cane, but the civil war had a devastating effect on production, and throughput in the1998 season was a mere 97 745 tons.

The Technical Management Department of Tongaat-Hulett Sugar was appointed to carry out the design and detailed engineering for the rehabilitation of the mill to a nominal throughput of 120 tons cane per hour, with a view to a possible future doubling of capacity. The scope of the rehabilitation included upgrading of boilers, a new heavy duty shredder, a new 6 m wide diffuser, modification of the evaporator station, a new 42 m^3 batch A-pan, a new 43 m^3 continuous C-pan, two new 120 m^3 vertical crystallisers, two new 1 500 kg batch centrifugals and four new 1 300 mm continuous centrifugals, as well as the refurbishment of most of the existing plant. The boiling house would be arranged to produce VHP sugar, using a threeboiling system with graining of A-pans and the use of C-magma for B-seed. In addition, the process of recycle of clarifier mud to the diffuser was selected, obviating the need for refurbishment of the filter station or ancillaries.

While various areas of the process design presented interesting challenges, one of the more absorbing came from an unexpected quarter – the evaporator station. Although evaporator design is ostensibly a routine exercise, the specifics of the Xinavane design forced consideration of the subtleties of evaporator design optimisation.

A preliminary evaluation of the evaporator station indicated that, irrespective of the condition of the vessels, the existing station design was not appropriate for the expected duty in the refurbished factory. In particular, the first effect area was clearly too small and the distribution of heating surface between the vessels in the tail was far from optimum. This discrepancy can probably be explained by the following changes, which are part of the refurbishment and significantly affect vapour bleed requirements:

- the elimination of the use of exhaust steam for boiling pans (previously available for use on two calandria pans)
- the scrapping of old coil pans which used steam at 400 kPa(g)
- a changed boiling scheme where B-sugar is fully remelted rather than being bagged
- higher levels of imbibition (selected to achieve higher extraction).

A further factor is that the existing evaporator station was modified during the civil war years, with the modifications defined by vessels that were available from other non-operational mills.

A detailed investigation into the design of the evaporator station was clearly required. It must be emphasised that evaporator station design cannot be conducted independently but is very closely linked to overall factory steam demand and the requirements for fuel economy.

Requirements of evaporator station design

On first consideration, it may seem that the requirement of an evaporator station is simply to remove water from juice to produce syrup. However, more detailed consideration will identify a significant number of requirements and constraints. Good evaporator station design involves balancing conflicting requirements and constraints while attempting to approach each of them as closely as possible.

The major requirements are:

- Evaporate the required quantity of water from clear juice to produce syrup at the appropriate brix for pan boiling.
- Condense all exhaust steam from the turbines (both prime movers and turbo alternators), avoiding blow-off and allowing a sufficient let-down from HP to exhaust (to allow exhaust steam pressure control).
- Have an efficiency designed in conjunction with the rest of the factory to eliminate (or at least minimise) either unwanted bagasse surpluses or the need for supplementary fuel (i.e. achieve a 'fuel balance').
- Supply vapour bleeds at the required quantities and pressures to meet the process demands of other sections of the factory.
- Supply the required quality and quantity of boiler feed water, primarily from condensed exhaust steam, but supplemented with other acceptable condensates.
- Act as a reactor for the destruction of starch when suitably dosed with the appropriate enzyme (not necessary in diffuser factories).

These must be achieved subject to the following constraints:

- The evaporator design must facilitate stable operation and control.
- The thermal degradation of sucrose and reducing sugars must be minimised.
- The capital cost must be minimised – a major factor in achieving this being the optimum distribution of heating surface between effects.
- The design should be robust, i.e. it should continue to perform acceptably over a reasonable range of operating conditions.
- The design should be compatible with future expansion plans.

Requirements of the Xinavane evaporator station

The first step in determining the requirements of the Xinavane evaporator station was to perform detailed steam balances over the entire factory. This was done using a computer program called SLOB (Steam Load Overall Balance) which was developed in-house by Tongaat Hulett Sugar (Rein and Hoekstra, 1994). These calculations were able to take into account factors specific to Xinavane that make it significantly different from the average South African sugar factory, viz:

- a low cane crush rate (average of 120 tons cane/h)
- lower efficiency boilers (2 x 30 ton/h Dutch oven type boilers)
- low HP steam pressure (2 100 kPa(a))
- lower efficiency turbines
- an unreliable electricity supply from the national grid
- a market for generation of electrical power (for irrigation)
- the use of local trees as the supplementary fuel source.

Unfortunately, because of the decline in performance of the mill during the civil war in Mozambique, there is limited quality data on plant performance and many 'best estimates' have been necessary as the basis for calculations of expected performance.

Taking these factors into account, steam balances for a range of expected operating conditions highlighted the following points specific to Xinavane.

When operating with a quadruple effect evaporator (V1 bleed only):

- supplementary fuel would be required even during the high fibre portion of the season
- the export of power would be possible without the need to blow off exhaust steam
- a reasonable quantity of HP to exhaust let-down would facilitate exhaust steam pressure control.

When operating with a quintuple evaporator (with V2 bleed for diffuser and primary juice heating):

- there would be a fuel shortage only during the low fibre portion of the season, with a bagasse surplus during high fibre periods
- the maximum generation of electricity for export would result in exhaust steam blow-off
- during periods of low fibre throughput, there would be very little HP steam to let down to exhaust which could result in unstable exhaust steam pressure control.

The difficulty in deciding between these two options is compounded by the possibility that the fuel shortage could be eliminated by an expansion in the near future, doubling the capacity of the mill. Preliminary calculations indicated that the lower specific steam demand of a larger factory would eliminate the need for supplementary fuel even when operating a quadruple evaporator. The added expense of creating a quintuple effect evaporator as part of the refurbishment would then be particularly difficult to justify, unless the design was fully compatible with the expansion.

Given these uncertainties, it was necessary to generate alternative designs for refurbishment of the existing evaporator station at Xinavane as either a quadruple or quintuple effect evaporation station. To evaluate the suitability of both of these designs for future expansion, it was also necessary to design evaporator stations for the expansion. This includes further possibilities since the benefits of generating export power for irrigation would require a quintuple evaporator if a condensing turbine proved economic or a quadruple evaporator if the condensing turbine was not an economic option.

Design of an evaporator station

Tongaat-Hulett Sugar has for many years used a computer simulation program (known as Program for Evaporator Simulation and Testing, or PEST for short) for the design and evaluation of evaporator stations. This program was developed in-house (Hoekstra, 1981) and provides detailed calculations which avoid many of the simplifying assumptions of evaporator calculations used in standard sugar texts describing evaporator calculations (Hugot, 1986). While PEST or other such programs will handle the details of the calculations, it is important for the evaporator designer to understand the principles of evaporator operation and the underlying calculations to use the program effectively. Elucidating these principles does, however, require using many simplifying assumptions.

A simple quadruple evaporator station (with vapour one bleed only) is shown in Figure 1, as the basis for the following discussion.

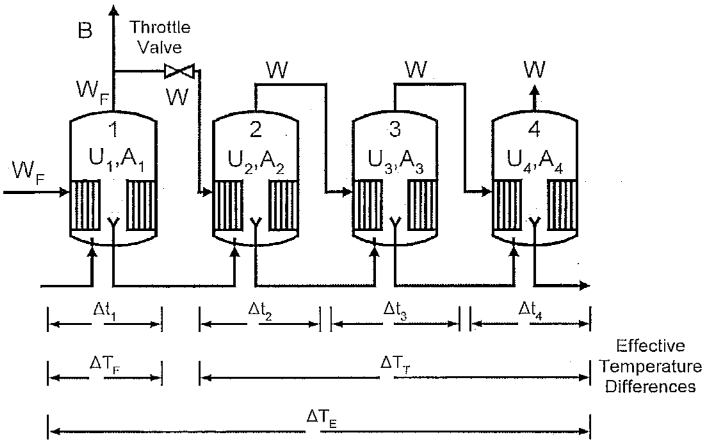

Figure 1. Representation of quadruple evaporator station with V1 bleed.

Fundamentals of heat transfer

The fundamental heat transfer equation which describes how heat is transferred across a heating surface is:

$$Q = U \cdot A \cdot \Delta T$$

where Q is the heat transferred in W

U is the heat transfer coefficient in $W/m^2/K$

A is the heating surface area in m^2

and ΔT is the temperature driving force in K.

In the case of an evaporator, ΔT is the difference between the saturated temperature of the steam in the calandria and boiling temperature of the liquid. The convention used in this work is to calculate A and U based on the outside diameter of the evaporator tubes and the distance between the tube plates. This formula clearly shows the equivalent influence of the heat transfer coefficient, U, and the heating surface area, A, on heat transfer. A 10% drop in heat transfer coefficient is directly equivalent to a 10% loss of heating surface area.

The evaporation rate W in kg/s can be calculated from the heat transferred as:

$$W = \frac{Q}{\lambda}$$

where λ is the enthalpy of evaporation in J/kg.

This assumes that heat losses are negligible and that there is no sub-cooling of condensate below its saturated temperature.

Principles of multiple-effect evaporation

The three principles of multiple-effect evaporation originally espoused by Rillieux (the pioneer of this technique) are (Spencer and Meade, 1945):

First principle	In a multiple-effect evaporator, for each kilogram of steam used, as many kilograms of evaporation will result as there are units in the set.
Second principle	If vapours are withdrawn from any unit of a multiple-effect evaporator to replace steam in a concurrent process, the saving of steam will be equal to the amount of vapour so used divided by the number of units in the set and multiplied by the sequence position of the unit from which the vapour has been withdrawn.
Third principle	In any apparatus in which steam or vapour is condensed, it is necessary continuously to withdraw the accumulation of non-condensable gas which is unavoidably left in the heating surface compartment.

The first and second principles are useful approximations which relate to the efficiency of evaporation but ignore the effects of juice flashing and variations in enthalpy of vaporisation (latent heat) with temperature. The nomenclature used in Figure 1 is based on the assumption that these principles are true.

Distribution of temperature driving force over evaporators

The temperature driving force available for achieving the required evaporation is the difference between the saturated temperature of the exhaust steam and that of the vapour in the final effect. The exhaust steam pressure is normally selected as 200 kPa(a) (being a compromise between the requirements for power generation and evaporator heating surface requirements). Smith and Taylor (1981) have shown that the optimum pressure for final effect vapour is between 16 and 20 kPa(a). This total available temperature difference will be reduced by the elevation of boiling point of the juice in each effect as a consequence of concentration and hydrostatic head. The net or effective temperature difference will then be distributed between the effects as per the heat transfer equation.

Effect of quantity of vapour bleed on evaporator station capacity

Detailed evaporator calculations on many practical evaporator stations in sugar factories have shown that increasing the quantity of vapour bleed will increase the evaporation capacity of the evaporator station. This increase in capacity will be associated with a decrease in bleed pressure. This phenomenon is not a natural consequence of multiple effect evaporator stations but only occurs when the effects before the bleed have a higher combination of area and heat transfer coefficient than the effects further down the evaporation train. Appendix 1 gives a derivation of this principle for a quadruple evaporator with vapour one bleed only. Simply stated, if we consider $\frac{1}{U \cdot A}$ to be the resistance of an evaporator effect to heat transfer, an increase in bleed will increase the evaporator capacity if the resistance of the first effect is less than the average resistance of the effects in the tail.

Effect of condensate flash on evaporator station capacity

In contrast to the effect of vapour bleed on capacity, the return of condensate flash into vapour streams will normally increase vapour pressures, and therefore reduce capacity but improve steam utilisation efficiency. This effect is, however, usually small.

The use of vapour throttling

Vapour throttling (normally used after the last vapour bleed) can be used as a control variable to reduce evaporator capacity without affecting evaporator efficiency. This will reduce capacity while increasing bleed pressures as opposed to the alternative of reducing capacity by reducing exhaust steam pressure (which will reduce bleed pressures). Throttling can be thought of as consuming driving force but not steam.

Optimal distribution of heating surface

Vessel area prior to the vapour bleeds should be installed to provide the required bleed pressures. Excess area installed here will result in bleed pressures above the required minimum values and, although this will increase the evaporator capacity (by driving the tail harder), the extra area would have been more effective had it been installed in the tail.

For effective distribution of heating surface area between the effects in the evaporator tail (i.e. after the vapour bleed or bleeds) Buczolich and Zadori (1963) provide guidelines for the optimum distribution of heating surface, as summarised by Hoekstra (1981).

The criterion for optimum distribution of heating surface is that the ratio of heating surface to effective temperature driving force should remain constant for each effect.

Expressed mathematically:

$$\frac{A_i}{\Delta t_i} = C$$

where i represents each effect and C is an arbitrary constant, termed here the area efficiency criterion.

Since heat transfer coefficients normally decrease towards the last effect, causing temperature differences to increase, the heating surface area will need to increase down the tail for effective use of installed area. On this basis existing evaporator stations with equally sized vessels in the tail indicate a design that is not optimal.

Design for the refurbishment of Xinavane evaporator station

Existing evaporator station

The existing quadruple effect evaporator consists of the following vessels:

Effect	Type	Area (m^2)
First	Semi-Kestner	1 523
Second	Robert	703
Third	Robert	402
Fourth	Robert	877

Preliminary calculations showed this station to have significantly less than the required capacity. In particular the first effect area was too small to provide an adequate bleed pressure and the distribution of heating surface between the effects in the tail was far from optimal. The heat transfer coefficients (listed below in Table 1) used in these calculations, and those for all modified configurations are based on extensive measurements by Tongaat-Hulett Sugar over many years and represent practically attainable design figures.

Table 1. Heat transfer coefficients used in evaporator simulations.

Effect	Heat transfer coefficient (kW/m²/K)	
	Quadruple effect	Quintuple effect
First	2,5	2,5
Second	2,2	2,5
Third	1,7	2,0
Fourth	0,7	1,5
Fifth	----	0,7

Refurbished quadruple effect evaporator

The design for the refurbishment of the quadruple evaporator was investigated in detail on the basis of either replacing the first effect vessel with a new Kestner type evaporator or converting the existing vessel into an (expanded) Kestner. The existing Robert vessels were to be retained.

The estimation of vapour bleed quantities is dependent on a number of operating practices and without established operating norms, a range of assumptions are necessary. Given this uncertainty in the quantity of vapour bleed required, a number of simulations were undertaken to estimate the first effect area that would be required as a function of vapour bleed (V1 bleed only) varying between 25% and 35% on clear juice flow, the best estimate being 31%. This was done for both the existing configuration of vessels in the evapora-

Table 2. Comparison of first effect area requirements for original and swopped sequences of evaporator vessels in the tail.

V1 bleed quantity (% CJ)	Original sequence of vessels Area (m^2): (as below): 703 : 402 : 877			Swopped sequence of vessels Area (m^2): (as below): 402 : 703 : 877		
	1st effect area (m^2)	V1 bleed pressure (kPa(a))	V1 throt. Δ P (kPa)	1st effect area (m^2)	V1 bleed pressure (kPa(a))	V1 throt. ΔP (kPa)
25	4 098	173,8	0,0	2 500	162,4	0,0
27	2 929	165,4	0,0	2 054	154,9	0,0
28,3 *	------	------	------	1 850	150,0	0,0
29	2 316	157,3	0,0	1 875	150,0	2,5
30,9 +	1 957	150,0	0,0	------	------	------
31	1 962	150,0	0,5	1 950	150,0	9,7
33	2 037	150,0	7,8	2 026	150,0	16,5
35	2 114	150,0	14,8	2 103	150,0	23,1

* Minimum first effect area for swapped sequence
\+ Minimum first effect area for original sequence

tor tail and that with the duties of the second and third vessels swopped around. A minimum (V1) bleed pressure of 150 kPa(a) was specified to provide for the requirements of the pan floor. A summary of these simulations is presented in Table 2 and Figure 2.

To demonstrate the use of the area efficiency criterion, Table 3 gives details of the evaporator simulations which require the minimum first effect area.

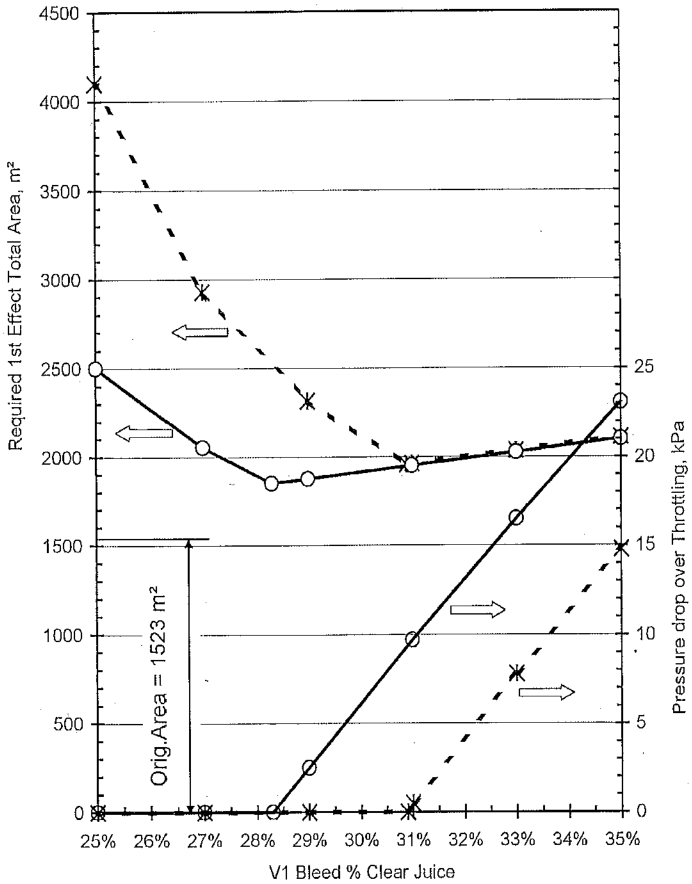

Figure 2. Effect of V1 bleed % clear juice on first effect area.

The area efficiency criterion shows that the distribution of the area down the evaporator tail is not ideal with the present arrangement of vessels. The range of the area efficiency criterion in the tail is reduced from 81 to 36 by swopping the duties of the second and third effect vessels, a significant improvement.

The full benefit of an effective distribution of heating surface in the tail might not have been evident if the sensitivity to the design assumptions had not been investigated. The results show clearly how the required first effect area is dependent on the design assumptions. In particular, if the bleed rate had been assumed to be 31% of the clear juice flow, a first effect area of approximately 1 960 m^2 is required, regardless of whether the sequence of vessels in the tails is left as at present or altered as indicated by the area efficiency criterion. The benefit of the swopped sequence in the tail is however very clear when lower bleed rates are considered. A design that is adequate for bleed rates as low as 25% on clear juice flow would be significantly more expensive if the second and third vessels were not swopped, as it would require approximately 1 600 m^2 additional first effect area. Interpreting this differently, a design without swopped second and third vessels that was adequate at a bleed rate of 31% on clear juice flow would be seriously under capacity at lower bleed rates. Vapour blow-off to atmosphere could address this issue, but at the expense of fuel efficiency and with the loss of good quality condensate. While vapour blow-off might be a useful operational technique in an emergency, it is unwise to include it as a necessary requirement during design.

An interesting aspect of the graphical presentation is that for both cases investigated (i.e. swopped and original sequences of second and third effect vessels) the graph shows two distinct sections. At lower bleed rates first effect area must be

Table 3. Effectiveness of area distribution in evaporator tail with original and swopped sequences of vessels.

Evaporator Performance with Minimum First Effect Area					
Arrangement of vessels in tail	Vessel characteristic	First effect	Second effect	Third effect	Fourth effect
Original Sequence	Area (m^2)	1957	703	402	877
	Area efficiency (m^2/K)	256	106	25	41
	Heat transfer resistance (K/MW)	0,20	0,65	1,46	1,63
	Ave. heat transfer resistance of tail (K/MW)		1,25		
Swopped Sequence	Area (m^2)	1850	402	703	877
	Area efficiency (m^2/K)	241	33	69	40
	Heat transfer resistance (K/MW)	0,22	1,13	0,84	1,63
	Ave. heat transfer resistance of tail (K/MW)		1,20		

installed to provide extra evaporation capacity, while at higher bleed rates, extra area must be installed to provide the required bleed pressure.

Based on these results, the selected design for a new vessel was to install a first effect with 2 200 m^2 of heating surface and swop the duties of the present second and third effect vessels. If converting the semi-Kestner to a Kestner was economic, the 2 500 m^2 vessel that would result from installing standard 7,2 m long tubes would be more than adequate. Both of these options can be shown to be compatible with designs for possible future expansion.

These results clearly demonstrate the importance of designs that are 'robust' with respect to design assumptions. The robustness is shown as being relative to the assumption of bleed rate, but could be equally interpreted as robustness to assumed first effect heat transfer coefficient.

Refurbished quintuple effect evaporator

The design for the creation of a quintuple evaporator was investigated on the basis of installing a new first effect Kestner vessel. The existing semi-Kestner and Robert vessels would be retained and their duties altered as necessary.

Computer simulations over a range of vapour bleeds did not show the same design sensitivity seen in the design of the quadruple effect evaporator. This is because in all instances the first effect area that is required to be installed is defined by the need to provide the required bleed pressure and not by the need to supply evaporation capacity. An alternative way of interpreting this is that there is more than sufficient area available in the existing vessels to be used for the second to fifth effects. The area efficiency criterion again indicates that the relative positions of the existing second and third effect vessels should be swopped for the most effective use of heating surface although this change does not reduce the required first effect area (i.e. there is more than sufficient area in the tail whether the vessel duties are swopped or not).

The excess capacity is shown in simulations of performance at design conditions as a large pressure drop across a valve throttling vapour to the third effect calandria, with greater throttling with the swopped sequence. In practice the extra capacity can be gainfully used by increasing imbibition on the diffuser and thereby increasing extraction if fuel supplies permit.

The configuration selected for a quintuple effect evaporator is:

Effect	Type	Area (m^2)
First	Kestner	2 000
Second	Semi-Kestner	1 523
Third	Robert	402
Fourth	Robert	702
Fifth	Robert	877

This configuration is also compatible with designs for possible future expansion.

Final selection of evaporator configuration

The final selection of either a quintuple or quadruple evaporator configuration for the refurbishment is dependent on detailed costings of these alternatives and had not been made at the time of writing this paper.

Equipment design for the refurbishment of Xinavane evaporator station

Although this paper is primarily about the principles of evaporator station design, it is also germane to mention here some of the specifics of evaporator equipment design as, without proper attention to these areas, the levels of performance assumed in the system design will not be met, and the station will fall short of requirements or exceed constraints.

The juice feed arrangements of the existing vessels was rudimentary and required modification. Proper distribution of the flash generated when the juice enters the next effect in a train significantly improves circulation in the vessel and therefore heat transfer performance. A feed ring external to the vessel with short feed stubs ending in carefully sized orifices ensures this distribution while allowing ease of cleaning/descaling as necessary.

High performance entrainment separators are essential to ensuring a reliable supply of good quality condensate for boiler feed. The existing evaporators at Xinavane were fitted with centrifugalvane separators (angled vanes around a central hub), with indifferent performance. Tongaat-Hulett has had success with an inhouse design of Vertical Chevron Plate (VCP) separator, which typically achieves contamination levels below 5 ppm, is free draining (nonclogging) and has been proven on all evaporator effects as well as pans. It is modular and can be arranged for cleaninginplace. New units of this design for all vessels is part of the refurbishment.

Correct sizing of the systems for removal of incondensible gases from the evaporator calandrias is crucial to achieve complete removal without excessive steam wastage. Accurate design in this area allows evaporators to be run without manual throttling of incondensible vents, with its associated margin for error.

The internals of the existing final effect external condenser are simple baffles. The refurbishment replaces these with a raintray design capable of achieving approach temperatures of less than 3 K, minimising the load on the injection water system and ensuring steady final effect absolute pressure. Effective cooling of incondensible gasses in the condenser is also important to avoid overloading the vacuum pump.

The latest design of Kestner type evaporator (first effect for either quin or quad) is fitted with juice recycle, in recognition of recent work at the SMRI and Tongaat-Hulett Sugar (Walthew and Whitelaw, 1996) which has confirmed the positive effect on heat transfer performance of increased tube wetting rates. The Kestner separator juice outlet will be fitted with a weir system which achieves preferential recycle up to a critical flowrate, beyond which recycle becomes proportional. This avoids the complexity of a pumping or control system on the recycle line.

The refurbishment includes automation of the evaporator station, using the 'cascade back' strategy. In this strategy, the preferred system for syrup brix control is a radio frequency probe, on the basis of which the rate of syrup extraction is throttled. The level in each vessel controls the feed rate to that vessel, with the exception of the first effect, as the separator is designed to operate without maintaining a juice level to minimise residence time and therefore degradation of the juice. Clear juice flow rate is therefore controlled on the basis of second effect level. The vapour throttle valve after the bleed is controlled on clear juice tank level.

Conclusions

The redesign of the Xinavane evaporator station has reaffirmed the place of the evaporator station at the core of a sugar factory design, filling as it does the simultaneous roles of juice concentrator, exhaust condenser, vapour utility supplier and boiler feedwater supplier, while playing a key part in the fuel / steam / power balance of the factory. In addition, the specifics of the Xinavane station have led to a review of the optimal distribution of heating surface in an evaporator train and the potential sensitivity of evaporator capacity to changes in vapour bleed rate.

This example has demonstrated that correct equipment design and 'common sense' sugar engineering are necessary but not sufficient in designing an optimum evaporator station and that pitfalls may trap the unwary. A fully robust station, able to meet all of the varied station criteria under any reasonable set of operating circumstances, can be achieved only by delving deeper into the detail.

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APPENDIX 1

The effect of vapour bleed on evaporator capacity can be demonstrated by the following analysis based on the simplifying assumptions of evaporator behaviour and equations detailed in the text of this paper. Consider a quadruple evaporator with vapour one bleed only, as shown in Figure 1 in the text of this paper. For simplicity (in line with the first principle of Rillieux) the quantity of evaporation taking place in the second, third and fourth effects is assumed to be equal. The temperature differences shown are the effective temperature differences available for driving the heat transfer. They are less than the available temperature difference between the temperature of steam in the calandria and that in the vapour space as a result of the elevation in boiling point of the juice due to concentration and hydrostatic head effects.

In this analysis we are particularly concerned with comparing the evaporation in the first effect with that in the rest (i.e. the tail) of the evaporator station.

For the first effect, the evaporation W_F can be expressed in terms of the effective temperature driving force ΔT_F as

$$W_F = \frac{U_1 \cdot A_1}{\lambda} \cdot \Delta T_F$$

For each effect in the tail the evaporation W can be expressed as

$$W = \frac{U_2 \cdot A_2}{\lambda} \cdot \Delta t_2$$

$$W = \frac{U_3 \cdot A_3}{\lambda} \cdot \Delta t_3$$

$$W = \frac{U_4 \cdot A_4}{\lambda} \cdot \Delta t_4$$

Defining the effective temperature difference across the whole tail ΔT_T as

$$\Delta T_T = \Delta t_2 + \Delta t_3 + \Delta t_4$$

it is possible to express ΔT_T as

$$\Delta T_T = \frac{W \cdot \lambda}{U_2 \cdot A_2} + \frac{W \cdot \lambda}{U_3 \cdot A_3} + \frac{W \cdot \lambda}{U_4 \cdot A_4}$$

and thus to express the evaporation in the tail W_T as

$$W_T = 3 \cdot W$$

and

$$W_T = 3 \cdot \frac{\Delta T_T}{\lambda \cdot \left(\frac{1}{U_2 \cdot A_2} + \frac{1}{U_3 \cdot A_3} + \frac{1}{U_4 \cdot A_4} \right)}$$

If we consider $\frac{1}{U \cdot A}$ to be the resistance of an evaporator to heat transfer, in analogy with electrical circuits, the simple rule of resistances in series being additive clearly applies.

The lengthy, rigorous calculations to demonstrate the effect of bleed on evaporator capacity can be avoided by the following approach:

An increase in bleed flow will cause a drop in the vapour one pressure, increasing the temperature difference across (and the evaporation in) the first effect. This increase in the value of ΔT_F, which is assumed to be dT, will cause an increase dW_F in the first effect evaporation which is given by

$$dW_F = \frac{U_1 \cdot A_1}{\lambda} \cdot dT$$

At the same time there will be an equivalent decrease in the value of ΔT_T, (since the total effective temperature difference across the evaporators ΔT_E remains constant). This will result in a decrease dW_T in the evaporation over the tail, which is given by

$$dW_T = 3 \cdot \frac{dT}{\lambda \cdot \left(\frac{1}{U_2 \cdot A_2} + \frac{1}{U_3 \cdot A_3} + \frac{1}{U_4 \cdot A_4} \right)}$$

Clearly, if the increase in first effect evaporation is greater than the decrease in tail evaporation, then increasing the bleed flow will increase evaporator capacity. This can be formalised by defining a 'bleed capacity factor', *BCF*, as

$$BCF = \frac{dW_F}{dW_T}$$

Thus,

$$BCF = \frac{\frac{1}{3} \cdot \left(\frac{1}{U_2 \cdot A_2} + \frac{1}{U_3 \cdot A_3} + \frac{1}{U_4 \cdot A_4} \right)}{\frac{1}{U_1 \cdot A_1}}$$

Continuing with the concept of $\frac{1}{U \cdot A}$ being the resistance of an evaporator to heat transfer, the *BCF* can be seen to be simply the ratio of the average resistance of the tail evaporators to the resistance of the first effect.

This 'bleed capacity factor' can be used to identify the following three conditions:

$BCF = 1$ Increasing vapour bleed has no effect on evaporator capacity. (This will occur, for example, if $U_1 \cdot A_1 = U_2 \cdot A_2 = U_3 \cdot A_3 = U_4 \cdot A_4$).

$BCF > 1$ Increasing vapour bleed increases evaporator capacity. This is the most common situation in sugar factories.

$BCF < 1$ Increasing vapour bleed decreases evaporator capacity.