

UNDERSTANDING THE IMPACT OF IMPROVED WETTING RATES ON THE PERFORMANCE OF MALALANE MILL'S FIRST AND SECOND EFFECT EVAPORATORS

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Abstract

The high V1 demand from the back-end refinery and striving to be more energy-efficient has initiated an investigation into the evaporator performance of the Malalane sugar mill. Numerous factors, such as sufficient steam pressure, evaporator tube cleanliness and heat transfer area, have an impact on the performance of an evaporator. However, with the wetting rates of the first-effect vessels being as low as 20 kg/h/tube, it was obvious that this problem needed to be solved first.

Research has shown that an increased wetting rate improves the heat transfer coefficient, the specific evaporation rate and, therefore, the overall performance of the evaporator station. The installed evaporator configuration in the first- and second-effects was changed from a parallel configuration to a partial series configuration in the 2020/2021 off-crop, in order to improve the wetting rate.

The impact that the increased wetting rate had on overall evaporator performance is presented in this paper.

Keywords: Wetting rate, evaporator, energy, syrup, inversion losses

Introduction

The evaporator station could be considered as the heart of a sugar factory (Dzirove *et al.*, 2014). It receives the steam from the boilers and uses it to concentrate the juice. The resulting vapour bleeds are used to meet many of the factory thermal energy demands for raw house and refinery use. The evaporators also produce condensate, which is returned and used as feed-water for the boilers. Some key indicators, like the heat transfer coefficients and wetting rates, are used to ensure that the evaporators perform optimally. The evaporator performance is key to the energy-efficient operation of a factory.

The Malalane sugar mill has a large back-end refinery. In the past, it has sometimes struggled to maintain adequate V1 pressure and has had to let down exhaust steam to supplement the V1 from the evaporators, which is an inefficient and costly operation. Important modifications were carried out to the Malalane evaporator station during the 2020/2021 off-crop period. These modifications comprised changing the first- and second-effect vessels from a parallel to a partial series operation, in order to provide higher wetting rates and to improve the evaporator's performance. The aim of these changes was to improve the heat-transfer coefficients of the evaporator vessels, with the primary objective being to eliminate the use of exhaust steam to the V1 let-down, in order to maintain the V1 pressure.

This paper presents a more in-depth assessment of the effects of the modification on the overall evaporator performance. The evaporator performance parameters for the 2020 and 2021 seasons have been compared, as part of this evaluation. The new configuration led to an improved evaporator performance without it having a measurable impact on the inversion losses.

Literature Study

Rein (2001) mentioned that an important consideration in the design of equipment relates to the flow characteristics. The consequences of a non-ideal flow in equipment will lead to a higher-than-necessary residence time and the associated sucrose losses. Rein stated that the proper design and operation can minimise the chemical degradation reactions in equipment that operates at a high temperature. The first- and second-effect vessels typically operate at high temperatures. The flow characteristics within the equipment is often overlooked, which leads to the actual behavior of the equipment differing from the way it is supposed to, or expected to, work.

A literature survey was conducted to evaluate the current state-of-the-art practices regarding evaporator residence time, the wetting rate and the issues affecting the heat transfer. Walthew and Whitelaw (1996) found that the heat transfer coefficient is increased by an increasing feed rate, whereby the formation of a laminar liquid layer is prevented, which reduces the heat transfer resistance. This is achieved by promoting turbulence through an increased feed-rate. The typical first-effect feed-rate value that is expected is 1kg/min/tube; and it is 0.75kg/min/tube for the second effect (Walthew and Whitelaw, 1996). Rein and Love (1995) suggested that a wetting rate of 80kg/tube/h is applicable to Kestner vessels, while Shah and Peacock (2013) showed that the higher internal flow that is achieved by the increased recirculation, improved the performance of Robert vessels.

In a study conducted by González *et al.* (1983), the juice flow was considered to be the variable that has the highest influence on the evaporation ratio. These results showed an increase of 0,32 kg/m²/h of evaporation per a 1000 kg increase of juice.

The degradation of sucrose in the evaporators is an important issue to consider, although it will not be covered in detail in this paper, except for a short overview. Purchase *et al.* (1987) investigated the sucrose degradation in different evaporators and mentioned that “if the temperatures and residence times are high enough to cause acid production from inverted sugars, then these conditions will also cause appreciable sucrose degradation”. The priority should therefore be to maintain lower temperatures and short residence times in the evaporators, to avoid acid formation. The above authors confirmed that when an appreciable inversion occurred, it was mostly within the first two effects, and that the highest rates of inversion were generally associated with evaporators in which a relatively large portion of the heating surface occurred in the first two effects. The efficient utilisation of energy, especially in the case of the Malalane Mill, requires a large number of vapour bleeds from the first two effects of the evaporators. Therefore, a large portion of the total evaporation must be done in these first two effects and at higher temperatures. The authors warn that if there is too much evaporation in these effects, there is a real danger of combining conditions of low pH and high temperature. This warning was considered and the results of the sugar degradation pre- and post- the modification will be discussed later in this paper.

Peacock (2007) recommended that it is best to operate an existing evaporator station at the final effect pressure that yields the optimum evaporative capacity. This contrasts with the ‘common sense’ solution to the problem, which only considers the impact of the final effect pressure on the final effect vessels themselves. Peacock showed that the level of sucrose degradation is minimised when the evaporative capacity of the station is at its maximum. Therefore, if the Malalane Mill can achieve a better evaporation rate across all the evaporators, the sucrose losses will also be minimised. Rackemann and Broadfoot (2016) found that the process variables that have the greatest influence on the sucrose losses early in the set are the residence time and juice temperature. The authors confirmed that large heating surface areas are unavoidable where large amounts of low-pressure process steam are required by the factory, and they proposed that, where possible, falling film- or Kestner-type evaporators should be considered, in order to reduce the residence times.

The plant modifications were completed, and the Malalane Mill was running by the time Munsamy (2021) published his work on the effect of the wetting rate on the undermined loss.

His investigation concluded that Kestner type vessels must be operated at a high feed-rate, because it improves the heat transfer and reduces the residence time and sugar degradation. The results of the Malalane evaporator reconfiguration will be compared and discussed later in the paper. Munsamy (2021) stated that the critical minimum wetting rate for a Kestner evaporator is "around 1.2 kg/min/m²".

Reconfiguration – Parallel to Partial Series

The Malalane evaporator station is made up of a quadruple effect, consisting of a Kestner, two semi-Kestners and a Robert vessel in the first-effect. There are four Robert vessels in the second effect, two Robert vessels in the third effect, and one Robert vessel in the fourth effect. The evaporator station has the flexibility to by-pass any evaporator vessel at any point in time, which allows a vessel to be taken offline for chemical and mechanical cleaning every day.

Parallel configuration

The Malalane evaporator parallel juice configuration (for the 2020 season) is shown in Figure 1.

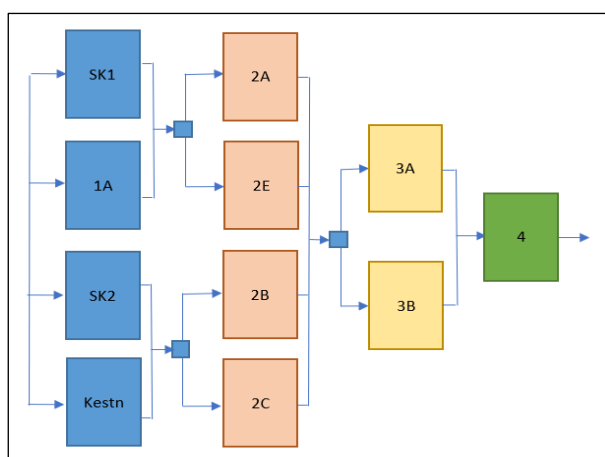


Figure 1. Evaporator juice configuration – parallel (2020 season)

The clear juice is distributed with a ratio control to SK1, SK2 and 1A, where the Kestner has a set flow of 100m³/h. The juice out of the SK1 and 1A is distributed via a splitter box to 2A and 2E in parallel (the south line), and the juice out of SK2 and Kestner is distributed via a splitter box to 2B and 2C in parallel (the north line). The juice out of the second-effects is distributed to 3A and 3B in parallel, also via a splitter box, and thereafter, the juice flows to the fourth effect.

Partial Series configuration

Juice pipe modifications were carried out during the off-crop season of 2020/2021, and the new partial series evaporator juice configuration (2021 season) is shown in Figure 2. No vapour side modifications were required.

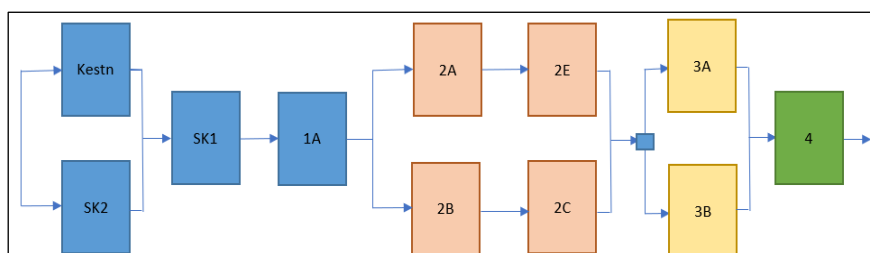


Figure 2. Evaporator juice configuration – partial series (2021 season)

The clear juice is ratio-controlled and fed in parallel, with individual flow meters, to Kestner and Semi-Kestner 2; thereafter, it flows in series to SK1 and then 1A. The juice to the second-effect is divided to flow in parallel to 2A and 2B, and thereafter, in series to 2E and 2C. The third- and fourth-effect juice flow configuration remained the same.

The aim was to get a 50/50 flow split between the north and south lines for the second effect; however, the operation encountered flow restrictions to the north line (2B side), which resulted in a 70/30 split and less efficient results. At the time of writing, the flow restrictions were still being investigated and addressed.

Results and Discussion

A more in-depth assessment of the effects that the evaporator configuration changes had on some relevant operating and performance parameters for the 2020 and 2021 season, have been compared.

Quite often, in simulation and models' average data is used. This does not reflect the actual operation during high- or low-flow periods. The end-result is then quite often not comparable to the actual factory results. In this paper, the specific representative days are compared, especially to illustrate the changed wetting rate.

The displayed graphs were formulated by using the JMP Version 15 statistical computer programme, and the smoothing tool was applied to the data to show the trends more clearly.

Wetting Rates and Heat Transfer Coefficients

The wetting rates were calculated, based on the measured data (the flow measurements and intermittent juice concentrations) for a typical normal operational day, for both seasons. The wetting rate data for the 2020 and 2021 seasons and each individual vessel in the first- and second-effects, are summarised in Table 1.

Table 1. Wetting rate (kg/h/tube) data for the 2020 and 2021 seasons of the first- and second-effect individual vessels

Season	First-effect Evaporators				Second-effect Evaporators			
	Kestner	Semi-Kestner 2	Semi-Kestner 1	Roberts 1A	Roberts 2A	Roberts 2B	Roberts 2C	Roberts 2E
2020	115	25	22	16	8	10	10	11
2021	115	44	56	39	21	11	8	25

Since changing the configuration of the first-effects to series (specifically SK1, SK2 and 1A) and increasing the feed-rate, the wetting rates have doubled. This wetting rate comparison was carried out at the same clear juice flow into the evaporator station.

The restriction to the second-effect evaporator (the north side) had an impact on the feed-rates to both lines. Higher feed-rates correlating with higher wetting rates were achieved on the south side (2A and 2E evaporators), whereby the lower feed-rates to the 2B and 2C evaporators decreased the wetting rate.

Studies have shown that an increase in the wetting rate will improve the heat transfer coefficient (Walthew and Whitelaw, 1996). The indicative heat transfer coefficient results for the 2020 and 2021 seasons are shown in Table 2; they were calculated by using a short-cut

manual method suggested by Rama and Munsamy (2008), taking into account the exhaust steam temperature, the juice inlet temperature and the boiling point elevation.

Table 2. Heat transfer Coefficient ($\text{kW/m}^2\cdot^\circ\text{C}$) data for 2020 and 2021 seasons of the first- and second-effect individual vessels

	First-effect Evaporators				Second-effect Evaporators			
Season	Kestner	Semi-Kestner 2	Semi-Kestner 1	Roberts 1A	Roberts 2A	Roberts 2B	Roberts 2C	Roberts 2E
2020	2.19	1.25	1.02	0.74	0.42	0.51	0.54	0.79
2021	2.11	1.91	1.37	1.01	0.66	0.50	0.21	1.07

The 2021 season heat transfer coefficients for SK2, SK1 and 1A improved significantly, which enabled the factory to run without the Kestner, while still meeting the factory's low pressure steam requirements and achieving the desired syrup Brix. This has proved that heat transfer coefficient increases were achieved with the increasing feed-rate, as stated by Walthew and Whitelaw (1996).

The second-effect evaporator's heat transfer coefficient improved for the south side line; however, as expected, the 2B and 2C evaporator's heat transfer coefficients were reduced with the lower feed-rates. The reduced flow also had an impact on fouling and will be discussed later in this paper.

Exhaust to V1 let-down valve output

The objective of improving the wetting rates, and the consequent improvement of the heat transfer coefficient, was to eliminate the use of exhaust steam to the V1 let-down, while still maintaining the V1 pressures. Figure 3 shows the output of the exhaust to the V1 let-down valve, for a similar period for both seasons.

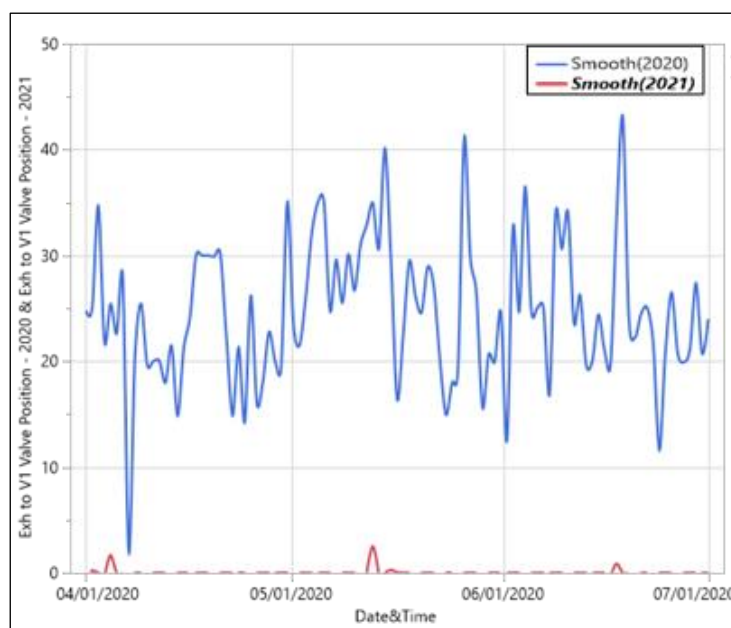


Figure 3. Exhaust to V1 let-down valve output for 2020 and 2021 season (Apr-June time period)

As an additional benefit, it was noted that the exhaust pressures were running lower in 2021, and that the V1 and V2 pressures were higher, when compared to the 2020 season; these are presented in Figures 4, 5 and 6, respectively. The higher V1 and V2 vapour pressures provide an improved capacity, as well as performance benefits, to the factory.

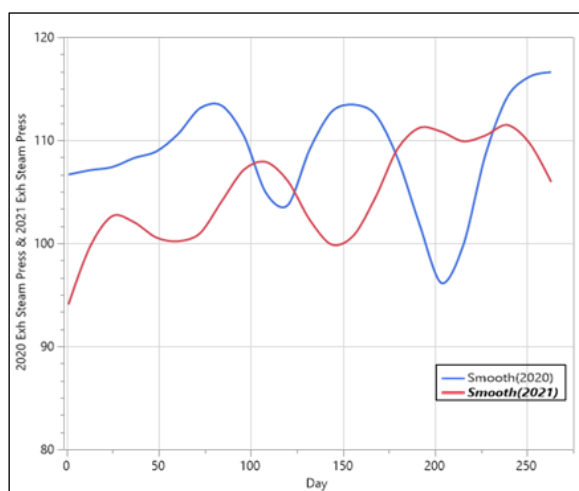


Figure 4. Exhaust steam pressure (kPa) for season 2020 and 2021

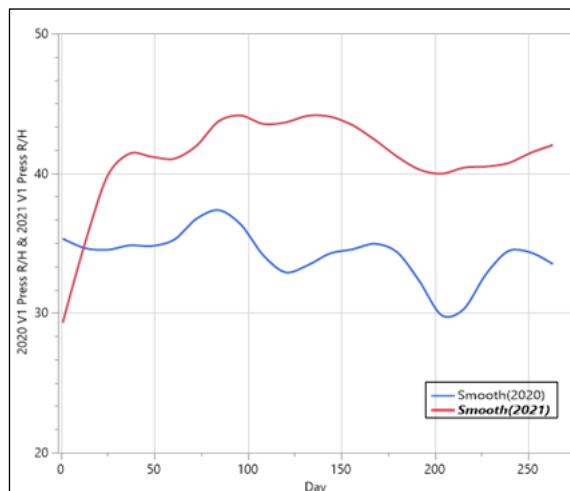


Figure 5. V1 Steam pressure (kPa) for season 2020 and 2021

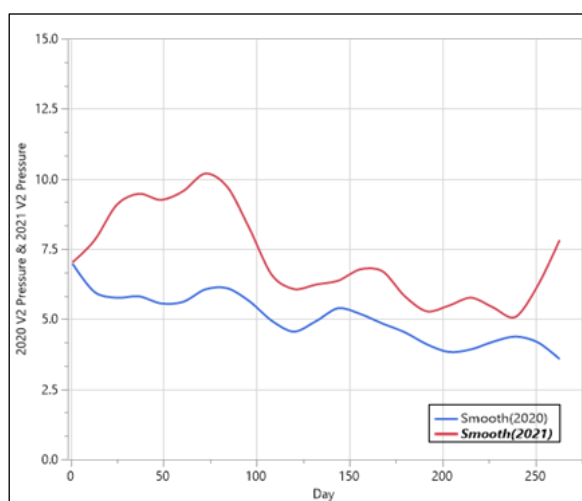


Figure 6. V2 Steam pressure (kPa) for season 2020 and 2021

Condensate % Return

The condensate % return process parameter is defined as the evaporator condensate flow return divided by the exhaust steam that is received, both streams are measured with mass flow meters. The target is for it to be above 100%, by ensuring that all condensed steam has been returned in the form of condensate, from the first- and second-effect vessels. A deficient supply in the return condensate will result in the need to make up the water for the boiler feedwater, which has an impact on the feed-water quality and steam efficiency.

In the 2020 season, when the exhaust to V1 let-down valve was open continuously, the condensate that should have been retrieved for the boiler feed-water was lost. Any exhaust in the V1 make-up that was used in the pan floor and juice heaters, was not recovered as boiler feed-water. Therefore, closing the exhaust to the V1 valve resulted in all the exhaust steam being used in the first-effect, which generated boiler condensate and improved the condensate recovery, as shown in Figure 7.

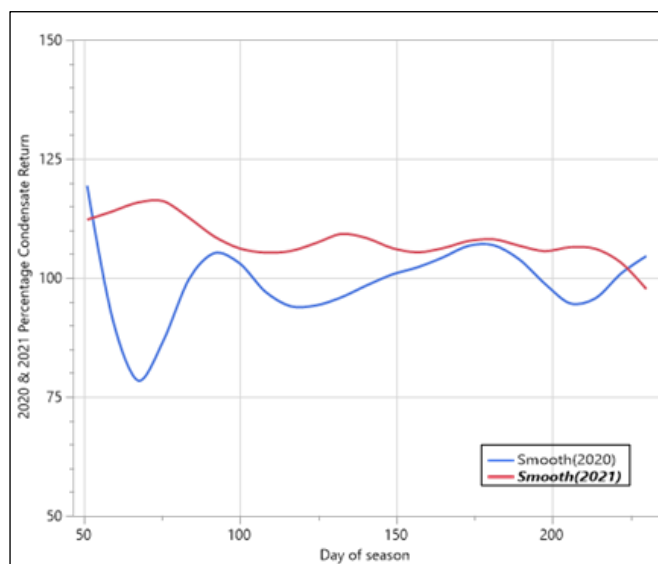


Figure 7. Condensate % return to boilers for seasons 2020 and 2021

Data from the beginning of the season, for both years, were excluded, due to difficulties with the flow meters. However, once the flow meters were repaired and the readings stable, it was evident that the condensate % return improved, and it has been more consistently above the target since the configuration was changed.

Syrup Brix

One of the evaporator requirements is to produce a syrup at the appropriate brix for pan boiling, by evaporating water from the clear juice (Love *et al.*, 1999). It was important to ensure that the syrup brix was still maintained after the modifications were carried out.

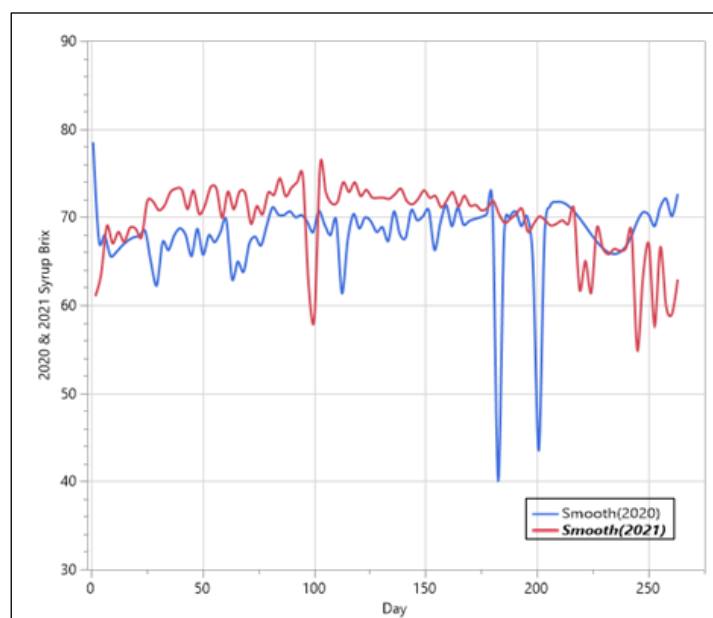


Figure 8. Syrup brix for the 2020 and 2021 seasons

As shown in Figure 8, the 2021 syrup brix of 70 was 1,5 units higher than the mean value of 68,5 for 2020. There were concerns about the too-high syrup brix values, especially if the syrup had to reach the sucrose solubility saturation limit (in the final effects). A decision was

made mid-way through the 2021 season to use this opportunity to increase the imbibition % fibre set point, which resulted in the additional benefit of improved extraction, as shown in Figures 9 and 10, respectively.

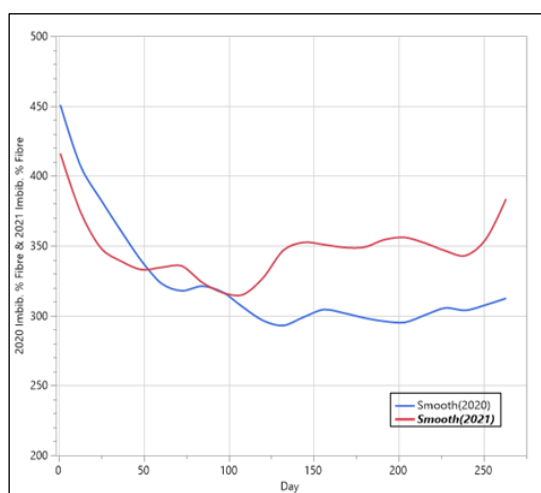


Figure 9. Imbibition % Fibre for seasons 2020 and 2021

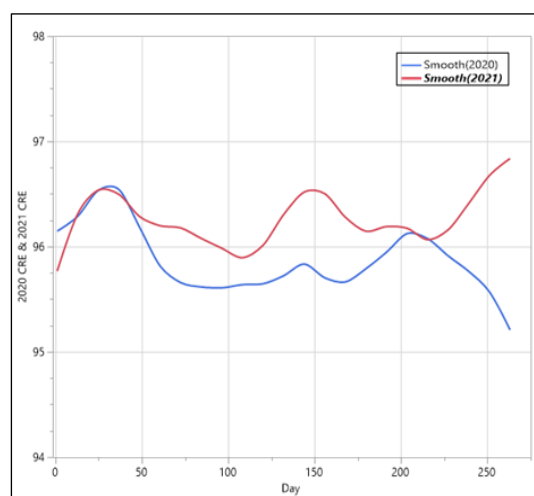


Figure 10. CRE for seasons 2020 and 2021

It is known that many variables impact the pol% extraction; however, an opportunity arose to increase the imbibition % fibre by 20%, which yielded a higher pol% extraction of 0,5 units.

Inversion Losses

Undetermined losses in the evaporator station resulted from sucrose inversion, which was accelerated by a low pH, high temperatures and a high residence time (Munsamy, 2021). The clear juice pH was controlled well during both seasons. The temperatures for the first-effect have reduced slightly and they increased slightly for the second effect, due to a change in the steam pressure. The apparent residence time in Table 3 was calculated by using the formula presented by Munsamy (2021), in order to understand the impact on the residence time, when changing the juice configuration from the parallel to the partial series.

Table 3. Apparent residence time (min) for first- and second-effect comparison for the 2020 and 2021 seasons

	2020	2021
1st effects	23	29
2nd effects (north line)	42	73
2nd effects (south line)	31	21

The apparent residence time for the first-effect evaporators has increased by six minutes, due to the partial series configuration. The apparent residence time for the north and south lines have been impacted differently, due to the uneven split of flow, as mentioned in the above sections. The true reflection of the impact of partial series juice configuration on the inversion losses was evaluated, based on the 'Syrup-clear juice purity' process parameter (Figure 11).

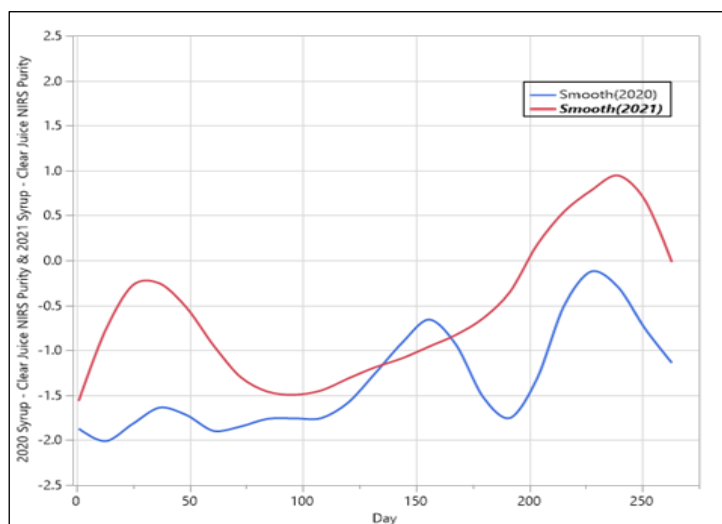


Figure 11. Syrup-clear juice purity results for 2020 and 2021 season

If the 'syrup-clear juice purity' parameter is below the target of -2, it indicates higher inversion losses across the evaporators. The 2021 season shows that this parameter improved from the previous year, which confirmed that a change in the juice configuration did not have a negative impact on the inversion losses across the evaporator station. The positive value for the 2021 season, from day 200 onwards, was not related to this project.

Evaporator Fouling

The Malalane Mill experienced several blocked tubes on the first- and second-effect evaporators during 2020. The drying-out of tubes is suspected to be due to the low-flow or unsteady-state conditions, and it leads to excessive scaling and blockages. Not all the blocked tubes in the evaporators were removed during the off-crop, and the 2021 season started with approximately 10% of the tubes still blocked.

Scaling is less severe when the juice velocities in the evaporator tubes are higher (Rein and Love, 1995). This statement was proven and observed by increasing the feed-rate of the first- and second-effect south-line evaporators, where the number of blocked tubes remained unchanged at the end of the 2021 season. The fouling in the north-line second-effect evaporators was found to be more severe during 2021, especially in the 2C evaporator, due to the lower wetting rates. The operations team had to de-scale and clean the saucer and 'down-take' twice during the season.

Conclusion

The changes to the evaporator configuration resulted in improved V1 pressures and the complete elimination of the use of expensive exhaust steam.

The new configuration also led to the following improvements:

- improved condensate returns to the boilers;
- consistent and high syrup brix;
- no blocked tubes were observed at the end of the season;
- improved cleaning cycles;
- the opportunity to run without the Kestner when the other vessels are available; and
- increased imbibition and extraction.

As far as could be determined, the changed configuration did not affect the inversion losses of the evaporators. The impact on the HP Steam % Cane could not be determined, due to other factors impacting the energy demands of the process.

The changed configuration confirmed the benefits, namely, the improved evaporator wetting rates and efficiency, as reported in the literature.

Acknowledgments

The authors would like to acknowledge the Malalane engineering staff for their assistance in modifying the plant, and the Malalane Management for giving us permission to publish the data. The authors are grateful to Mr. M Getaz for programming the modifications on the Sugars™ models, to help with the correct configurations and the decision-making process.

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