OPERATIONAL PAPER

KILLING-THE-JOULE: ENHANCING ENERGY EFFICIENCY THROUGH STRATEGIC AND PRACTICAL INITIATIVES AT THE HULETT SUGAR REFINERY

Reddy J, Rambukus Z and Maharaj N

Hulett Refinery, 444 South Coast Road, Rossburgh, 4072, South Africa

jesita.reddy@tongaat.com zyven.rambukus@tongaat.com nishan.maharaj@tongaat.com

Abstract

The Tongaat Hulett White Sugar Refinery, which is located in Rossburgh, Durban, is the largest stand-alone refinery in South Africa, with a rated throughput capacity of 80 tons/hour. In recent years, manufacturing entities have shifted their focus from solely achieving throughput targets to doing so in an energy-efficient manner. As climate change and global warming continue to receive heightened attention, they have become pivotal considerations for the long-term sustainability of businesses. In pursuit of sustainable manufacturing, the refinery has launched an integrated energy-efficiency programme under the initiative 'Killing-the-Joule'. Improving energy efficiency not only enhances environmental sustainability, but it also positively impacts a company's financial performance by reducing its coal consumption. In alignment with this objective, the refinery has implemented several initiatives that are aimed at boosting energy efficiency. The key areas of focus included the front-end (decolourisation) operations, particularly focusing on stabilising the dissolved solids concentration (brixes) through melt brix control and lime density stabilisation, as well as the back-end (crystallisation) operations and the boiler plant operations. This paper also introduces a parallel initiative – the Vapour Recovery Project, which captures previously-wasted flash vapour to heat carbonated liquor, thereby achieving additional steam savings and reducing the dependency on coal even further. The emphasis was placed on enhancing the reliability of the equipment and optimising the recovery of energy through capital projects that are aimed at energy savings. This paper presents an overview of the various projects and initiatives that were undertaken at the Rossburgh refinery. It highlights the effects of the continuous improvements, which demonstrates that it is a robust model for energy management in sugar refining.

***Keywords*:** Energy efficiency, sugar refinery, sustainability, operational optimisation, decolourisation, vapour recovery, boiler interventions

Introduction

The Rossburgh Sugar Refinery, which is recognised as South Africa's largest stand-alone sugar-processing facility, refines approximately 450 000 tons of sugar annually and has a name-plate capacity of 600 000 tons per annum. Unlike integrated sugar mills that typically utilise bagasse - a fibrous by-product of sugarcane - as a renewable fuel source, the refinery relies exclusively on coal for its thermal energy needs. This dependence on coal not only constitutes the second-highest cost component, but it also represents one of its most significant cost drivers. Consequently, improving energy efficiency has emerged as both a strategic necessity for its economic sustainability and an environmental imperative, in the context of the global and national decarbonisation efforts.

Traditional methods of energy optimisation include waste heat recovery from low-grade vapours for process-heating purposes (Mbohwa, 2013), multiple-effect evaporation and boiler efficiency optimisation through economisers, preheaters and air-to-fuel ratios and good operational control on the furnace conditions, as well as the elimination of rogue water into the processes that drive up the evaporation requirements (Elwardany, 2024; Lavarack *et al*., 2004). Some more exotic technologies incorporated within industrial processes include heat pump technologies that are used to step-up low-grade vapour (Chua *et al*., 2010); however, the total exergy dynamics of electrical and thermal energy must be considered for its economic viability. Lastly, a popular method that has also been used at the Hulett Refinery is the pinch technology, to optimise the heating requirements across a system (Tayfield & Hoekstra, 1998).

This paper examines the strategic and operational measures that were undertaken by the refinery to enhance the thermal efficiency of its refining processes. Commencing in the 2020/21 operational season, the refinery initiated a comprehensive turnaround strategy that encompassed the key focus areas, such as yield optimisation, energy management, digital transformation through information systems, workforce development and organisational culture enhancement. The outcomes of the various energy efficiency interventions that have been implemented since 2021 are presented below.

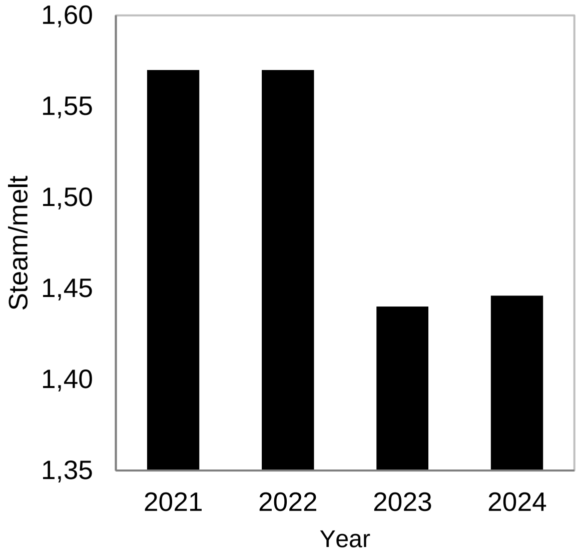

Figure 1. Steam-to-melt ratio – a reduction of 8.3% basis points from 2021

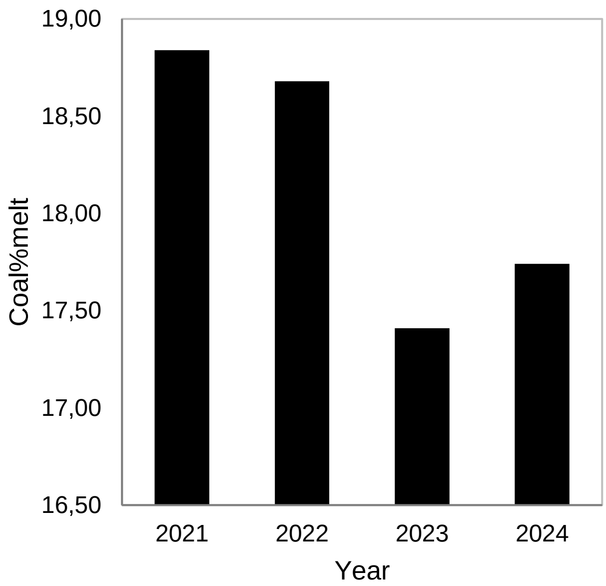

Figure 2. Coal%melt - a reduction of 6.3% basis points from 2021

Refining and energy flowsheet description

The refinery employs a conventional four-boiling scheme and has more recently integrated a fifth boiling stage into the local market blend for white sugar production. The run-off syrup from the pan house undergoes further concentration in a three-boiling partial remelt recovery system, in which the remelt is redirected to the main melting process. Thermal energy for the refining operations is supplied by two 31-bar boilers and a series of 14-bar Babcock boilers. A significant portion of steam is expanded through a turbine to facilitate electricity generation. Despite these efforts, the refinery remains a net importer of electricity to meet its complete energy demands. The performance of the process is evaluated by using a set of efficiency metrics, which are outlined below:

Steam to melt – This is the ratio of the total steam tonnage raised at the boiler plant to the total amount of raw sugar melted.

Steam to coal – this is the ratio of the total steam that is generated at the boiler plant, relative to the coal input to the boiler.

Coal % melt – this is the ‘bottom line’ metric for energy efficiency at the refinery. This measures the amount of coal used per ton of melt, and the goal at the refinery is to drive it as low as possible.

Figure 3 is a simplified flow sheet for refining and the energy demands per unit operations, with details given in Table 1.

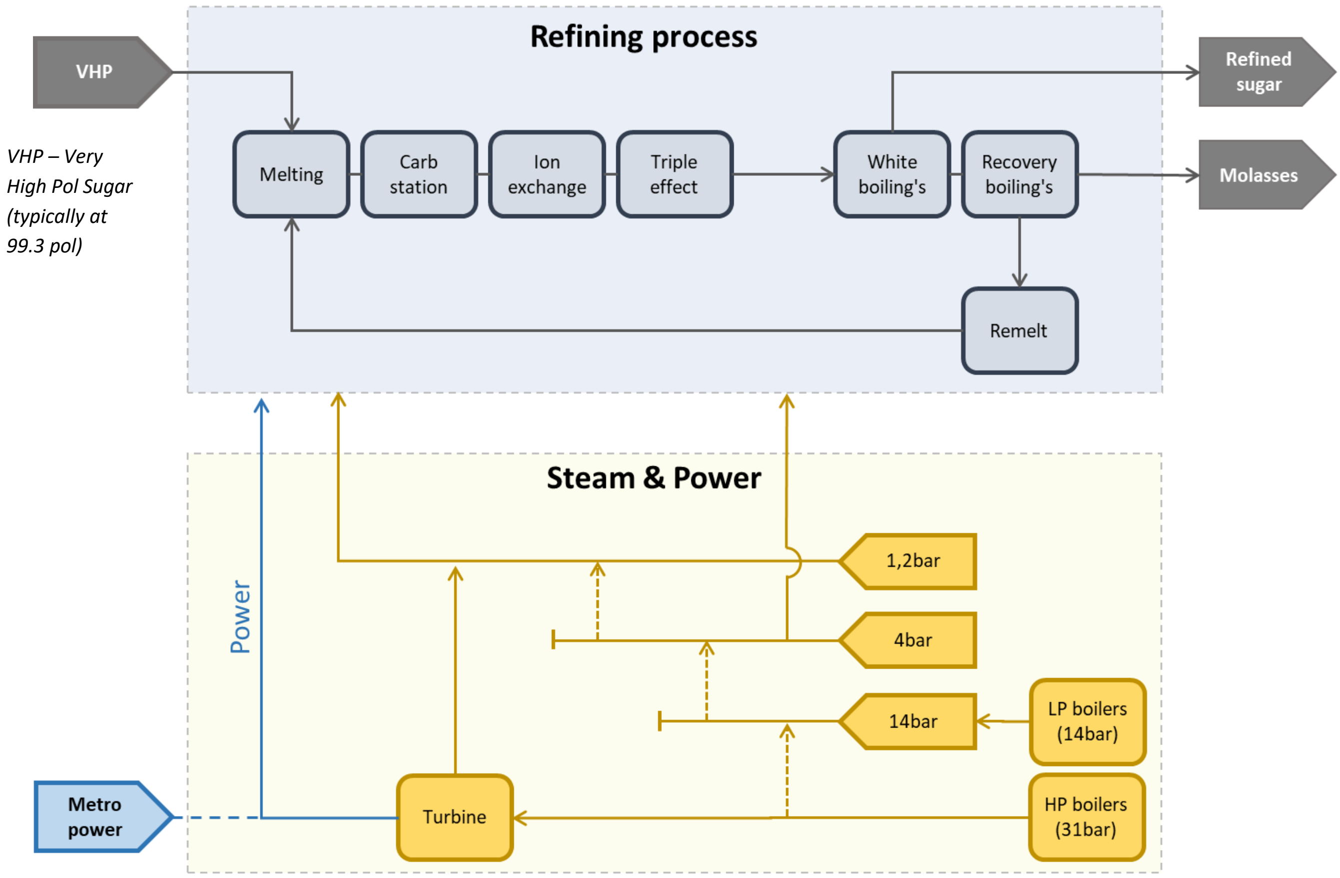

Figure 3. Simplified refining, steam and power flowsheet for the Tongaat Hulett refinery

Table 1. Unit operation's theoretical steam demand (both 120 kPa and 400 kPa) with a melt basis of 60 tph

Unit Operations	Exhaust - Ton/hr	% on melt	% Utilisation	Comment
Melting	0	0	0%	Heat of dissolution - V1 & V3 bleed from evaporators
Carbonatation & ion exchange	5	0,08	6.94%	Heating of carbonated liquor & hot-water heating
Evaporation	8	0,13	11.11%	Concentration to fine liquor
White pan house crystallisation	45	0,75	62.5%	5-boiling scheme
Recovery house crystallisation	10	0,17	13.89%	3-boiling scheme with partial remelt
Deaerator - boilers	4	0,07	5.56%	Boiler feed water
	72	**1,20**	**100%**	

A shifting operating paradigm

The operational experience accumulated over several years has demonstrated that an optimal performance in both the yield and energy efficiency is achieved when the refinery operates at, or near, its name-plate capacity of 600 kilo-tons per annum (ktpa), which is equivalent to approximately 80 tons per hour. This correlation is illustrated in Figures 5 and 6.

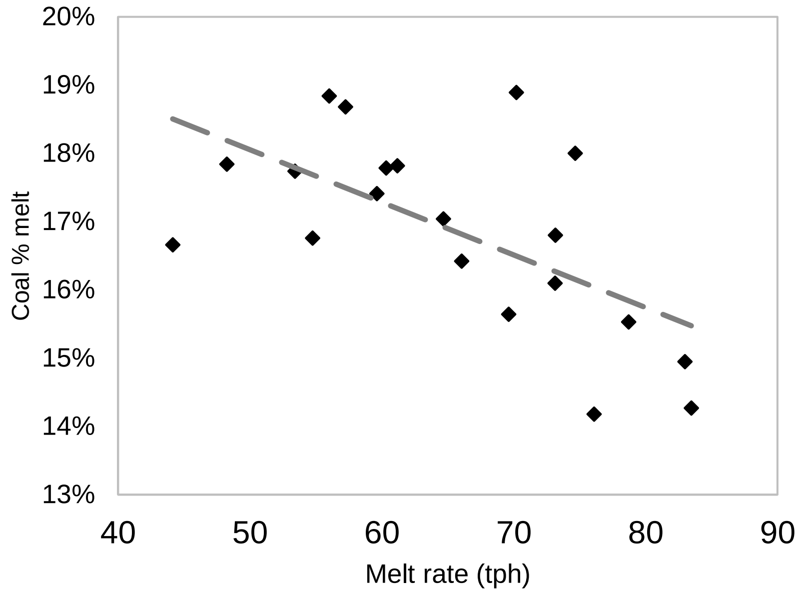

Figure 5. Long-term regression analysis of energy efficiency for the period 2005-2024

The short-term trend (Figure 6) covering a four-month period in the 2023 period also confirms a similar dynamic, i.e. poor energy efficiency results in low throughputs.

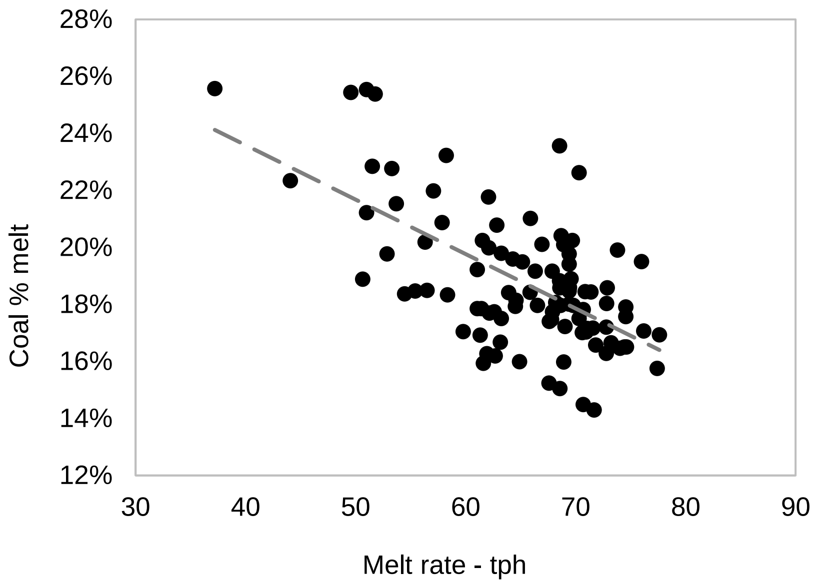

Figure 6. Short-term regression analysis for April to July 2023 – case study approach to energy efficiency for various melt rates

An analysis of Figures 5 and 6 suggests the presence of both fixed and variable loss components that influence the refinery's energy efficiency. Fixed losses may include factors such as radiant heat losses, extended residence time, which results in liquor cooling, and a consistent proportion of recycled solids (sweet water), relative to a reduced melt rate. Consequently, it can be inferred that optimising the throughput in relation to these fixed losses can significantly improve the overall energy efficiency.

This correlation between energy efficiency and throughput introduces a critical operational challenge, particularly in the context of the declining market demand for refined sugar, which is attributed to increased imports and shifting consumer attitudes towards sugar consumption. Currently, production hovers around 450 kilo-tons per annum, which is well below the refinery's name-plate capacity. In response, a key strategic priority for the refinery's leadership is to enhance energy optimisation across varying throughput levels and to develop a 'variable refining strategy' that aligns more closely with the market demand dynamics and that is energy-efficient at different market demand points.

A practical framework to manage energy

In developing a deeper understanding of the refinery's energy dynamics, the following model (Figure 7) reflects the myriad factors that directly and indirectly influence the energy efficiency performance paradigm. The following section highlights the various practical strategies implemented at the refinery.

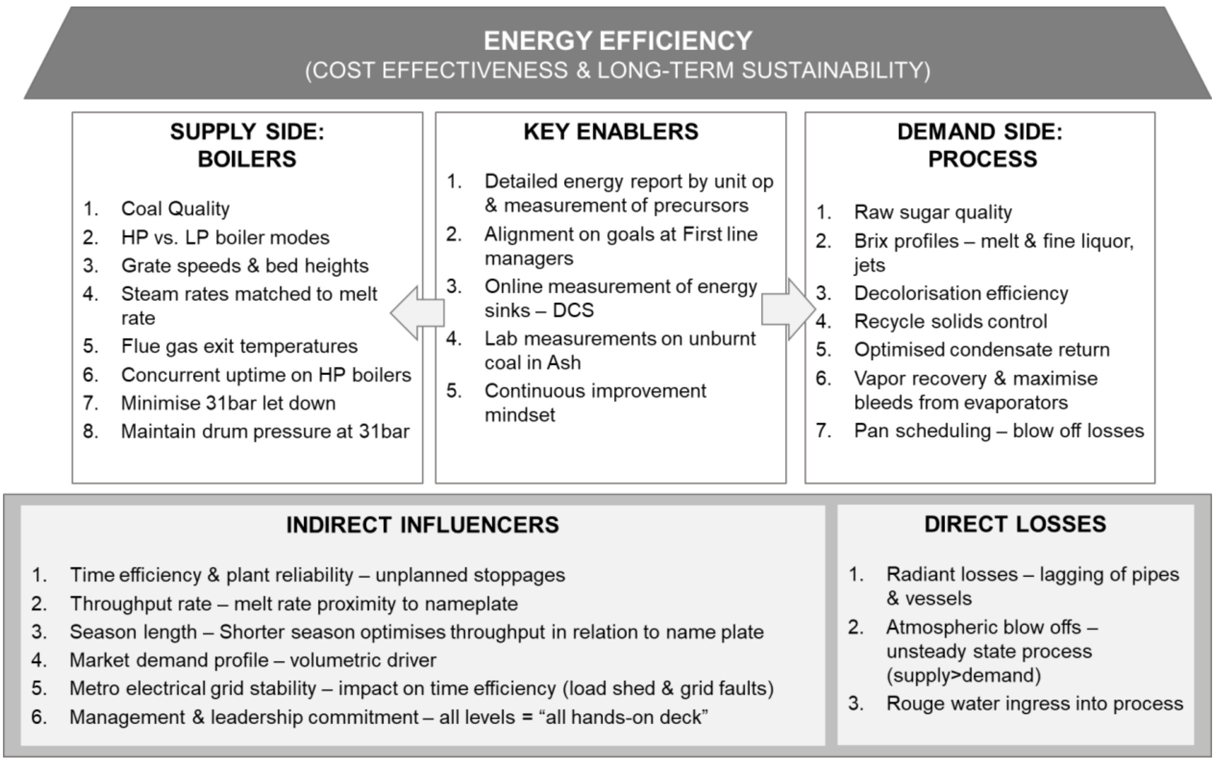

Figure 7. Working framework for energy efficiency at refinery

Practical interventions

Melt brix optimisation: driving energy efficiency at the source

Background

In sugar refining, the concentration of dissolved solids in the melter, which is commonly referred to as brix, plays a critical role in determining the energy demand of the subsequent evaporation stages. The initial stage of the refining process involves combining raw sugar with water in a four-compartment melter and applying heat to produce the 'melt solution'. Operating the melter at elevated brix levels minimises the volume of excess water that must be evaporated during the downstream processing, prior to the recrystallisation phase. This reduction in the water-load directly translates into decreased steam consumption. These findings are consistent with those of previous research, which demonstrated that the optimisation of melter operations can yield substantial energy savings (Bodija *et al*., 2020)

For the 2023/24 season, the average main melter brix was 67.4%. For the 2024/25 season, this increased to 68.7%. This 1.3% increase resulted in the evaporator station's steam consumption reducing from 9.36 tph to 7.95 tph, which was a 15% saving.

The means by which this was achieved is highlighted below:

Melter brix control enhancement

To achieve precise control over melter brixes, advanced instrumentation and control strategies are essential (Lorenz, 2008). Previously, the refinery utilised a Coriolis meter to control the brix of the melter. Based on the brix reading, the amount of water would be varied to achieve the brix set point. This Coriolis meter was installed on a slip-stream line from the outlet of the first compartment of the melter. The Coriolis meter was prone to blockages and it would frequently require intervention to unblock the lines (during which the melter brix would not be controlled). These instabilities would result in inaccurate melter brix readings and ultimately affect the downstream processes and energy efficiency. The instrumentation improvements included installing a microwave probe directly into the first compartment of the melter, thus alleviating the challenge of blockages.

Energy implications

Following the change of the brix measurement instrumentation from a Coriolis meter to a microwave probe, a high-brix melting trial was carried out to determine the optimum level of brix, which allowed for energy-efficient operations, whilst not hindering the throughput. The melter brix set point was increased to 72ºBrix which would effectively reduce the amount of water entering the evaporation stage and resulted in lower steam requirements.

The optimum brix that was achieved was 71%; anything above this resulted in flow issues being experienced downstream.

The quality of the incoming raw sugar played a crucial role in allowing the implementation of the high brix trial. During the 2021/22 season, the high dextran and low pol sugar resulted in increased flow and throughput restrictions.

Maintaining a consistent brix of 71ºBrix is the next step for improving the energy efficiency across the factory, as process instabilities have a cascading effect on the melter brix control.

Fine liquor brix optimisation

A major initiative aimed at optimising the energy consumption was the installation of a falling film triple-effect evaporator station downstream of the ion exchange units. Prior to this upgrade, the fine liquor was concentrated by using a double-effect Robert evaporator system, typically achieving a final brix of approximately 72ºBrix. With the implementation of the new system, the fine liquor brix supplied to the first boiling now consistently ranges between 76% and 78%. This significant increase in pre-concentration markedly reduces the energy required in the fine pans to bring the liquor to the graining point - approximately 83ºBrix - thereby improving the overall thermal efficiency in the crystallisation process. An effective 53% reduction in evaporator steam savings (% on melt) was achieved by using this intervention (Figure 8).

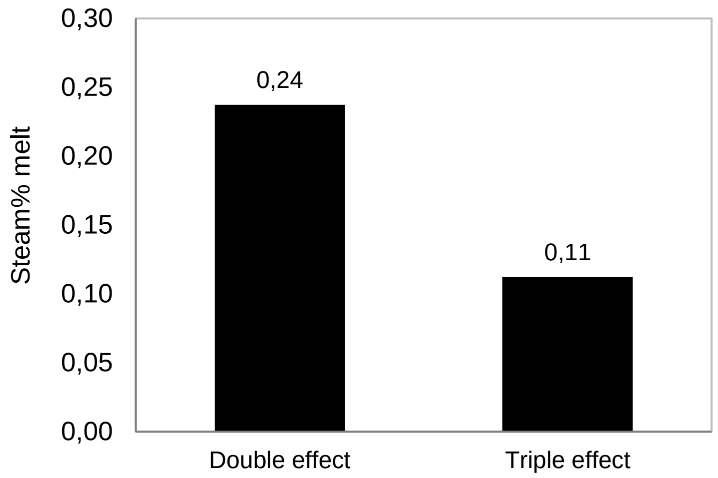

Figure 8. Reduction in steam requirements from the double effect to a falling film triple effect at fine liquor brix of 78% on 60 tph melt basis

Decolourisation optimisation

One of the critical factors in optimising the energy efficiency within the refinery is the reduction of reject sugar via the off-specification (off-spec) stream, which is commonly referred to as 'wet recycle solids'. Every ton of sugar rejected to the main melter effectively undergoes the entire refining process again, thereby re-consuming energy at multiple stages. In the 2019/20 season, the refinery implemented a third stage of ion exchange by using styrenic resin. This enhancement, in conjunction with an intensified effort to reduce the raw sugar colour from the supplying mills, resulted in a marked improvement in the fine liquor colour profile. The colour is measured in units of ICUMSA (International Commission for Uniform Methods of Sugar Analysis) and the improvement resulted in a drop in colour from approximately 450 ICUMSA to below 300 ICUMSA, thus enabling the consistent production and packaging of fifth boiling sugar, which contributes to a 3.2% reduction in recycle solids and an associated 3 percentage point decrease in the energy consumption, relative to the baseline.

Lime slaking optimisation

Background

Lime slaking is a critical process in sugar refining that involves the preparation of the lime slurry used in the carbonatation process (the first decolourisation step). A consistent lime quality is paramount for efficient impurity removal and for maintaining the efficiency of the process (Moodley *et al*., 2002). One of the feeds into the carbonatation process is slaked lime. Dry lime (CaO) powder is slaked (mixed with water) to yield milk of lime (a suspension of hydrated/slaked lime ($Ca(OH)_2$) in water. The water and lime are mixed to achieve a density that is usually between 1080 and 1100 kg/m^3. Density is an important factor, as a lower density will result in unnecessary melt dilution, whilst a higher density may result in pumping and handling difficulties. The density of the milk of lime is achieved by controlling the flow rate of water to the lime slaker. The combination of CaO and water is an exothermic process and, therefore, the density of slaked lime is achieved by indirectly controlling the temperature of the slaker. Water at approximately 65°C is required to achieve the desired slaked lime temperature of 90°C, and hence the density of the slaked lime. Samples of the milk of lime are tested in the laboratory to measure the density by simply dividing the mass of the sample by the volume of the sample. To achieve the right temperature, the flow-rate of the water is controlled via a control valve on the water line to the lime slaker. However, the temperature of this water was not constant, due to upstream process instabilities.

Slaked lime density control

Automating a heated water make-up stream to achieve the desired temperature of 65°C of water in the lime slaker ensures a consistent slurry density and temperature. Having a stable water temperature could lead to an improved reaction efficiency (Rein, 2007). The water temperature control into the lime slaker was automated by using a temperature-regulated control valve. This stabilised the slaked lime density within the target of 1080–1100 kg/m^3, improving the First Time Yield from 54% to 88%. The First Time Yield is a key performance metric that measures the proportion of units that are produced correctly and that meet the quality standard the first time, without needing to be reworked. This is shown in Figure 9. The consistent lime quality also improved the downstream process stability and brix control.

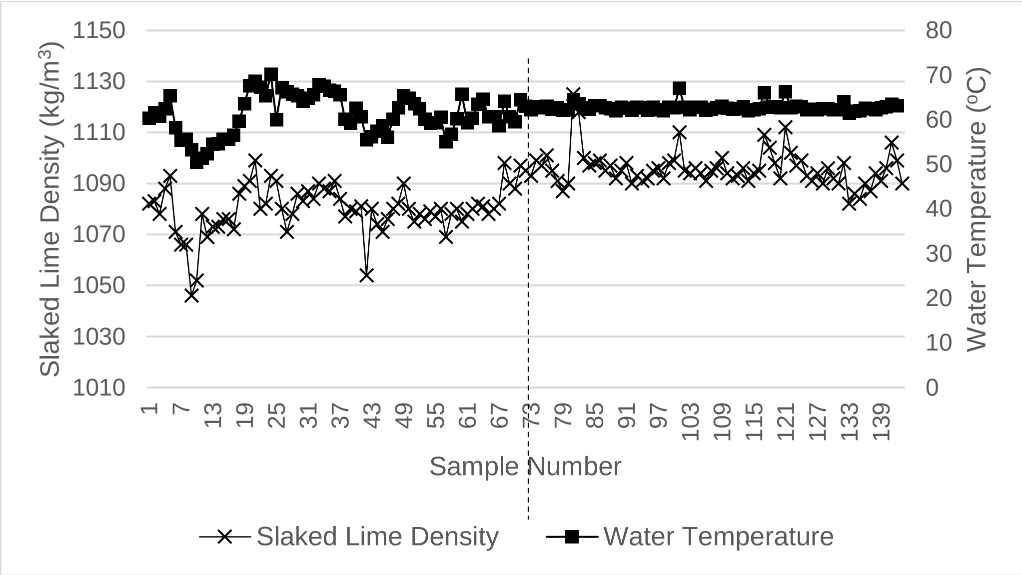

Figure 9. Slaked lime density and water temperature before and after automated control (indicated by the dotted line)

The vapour recovery project: capturing untapped energy and the application of pinch analysis

Background

In many industrial processes, including sugar refining, waste heat recovery presents a substantial opportunity for energy conservation. At the refinery, flash condensate vapour (from the pans and evaporators), which are often vented to the atmosphere, represents a loss of potential energy that can be harnessed for process heating. Implementing a vapour recovery system can capture this energy, which will lead to the improved overall efficiency and reduced coal consumption (Lavarack *et al*., 2004).

Process design

The vapour recovery project at the refinery involves redirecting this flash vapour from the condensate-receiving flash tank to heat carbonated liquor in a repurposed Robert evaporator. The heating of carbonated liquor was previously carried out in a saturator with a tubular calandria (known as the C-saturator) by using exhaust steam from the boilers. The Robert evaporator was decommissioned in 2018, when it was replaced by a triple-effect falling film evaporator.

This process therefore utilises the existing equipment, which has been retrofitted with new piping and control systems, to facilitate the efficient heat exchange. By utilising this flash vapour to heat carbonated liquor, the amount of exhaust steam that is required is reduced. The exhaust steam is thereafter only used as a top-up in the C-saturator, to heat the carbonated liquor to the desired temperature. This integration illustrates the process integration techniques that are aimed at minimising the energy demand by optimising the heat recovery (Figure 10).

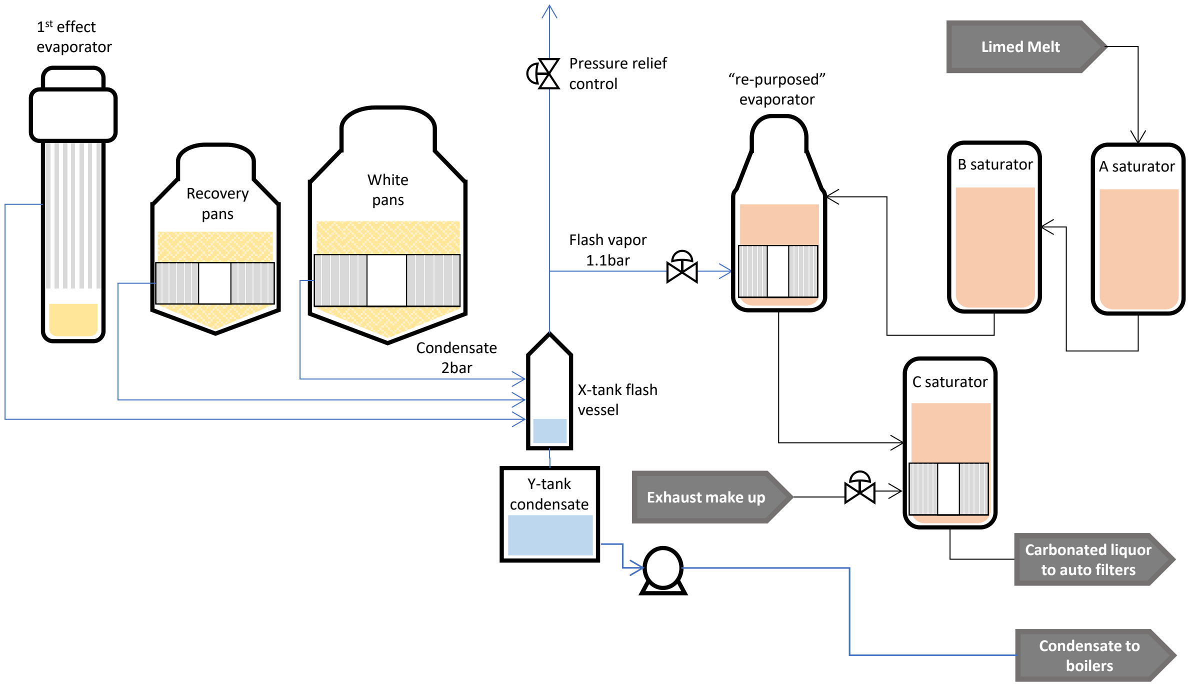

Figure 10. Schematic of the refinery waste heat recovery system

Control philosophy

Effective control strategies are critical for the success of the vapour recovery system. The implementation of control valves, temperature and pressure transmitters and automated control loops ensures that the system operates within the designated parameters. Supervisory controls are established to handle deviations, such as excessive liquor temperatures or pressure drops, thereby maintaining the system's integrity and safety.

Outcomes and savings

The implementation of the vapour recovery system has led to a significant reduction in steam demand within the C-saturator, which translates to considerable cost savings and a decrease in coal consumption. Prior to the vapour recovery project, the steam usage in the C-saturator averaged 3.95 tons/hour. After the implementation of the project, this figure dropped to 1.84 tons/hour.

To exemplify the drop in steam usage, the exhaust steam to the C-saturator, as a fraction of the total steam supply, is indicated in Figure 11. As illustrated, this figure dropped from 0.05 in the 2023/24 season to 0.03 in the 2024/25 season (after the implementation of the project).

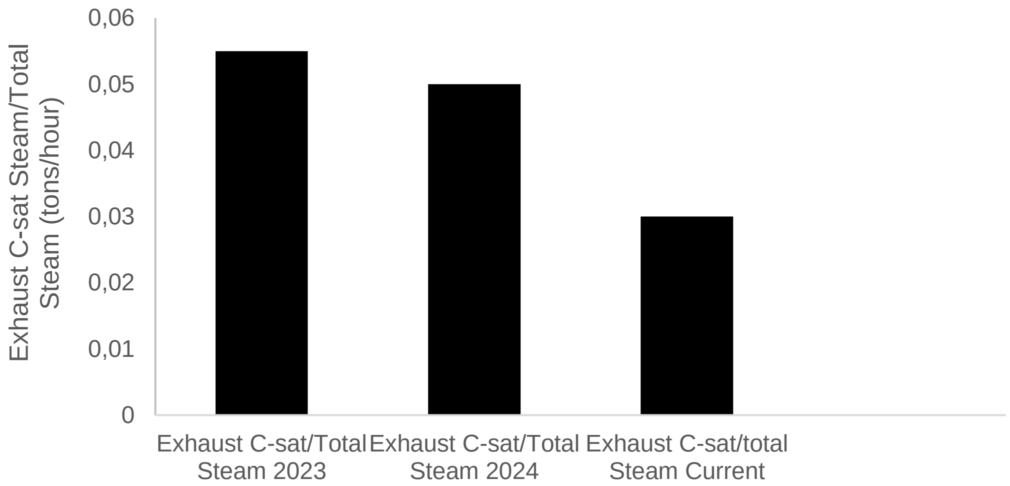

Figure 11. Exhaust steam to C-sat as a ratio of the total steam supplied – a comparison before and after the vapour recovery project

Boiler plant interventions

The boiler plant represents the supply aspect of the thermal supply chain and is an integral key success factor for refinery optimisation. The following aspects were optimised and remain the key focus area:

Reinstating economisers

This will be achieved by reintroducing an additional bank of economisers in the refinery's HP boiler, provided that there is a guaranteed improvement in thermal efficiency of the boilers.

Optimisation of the concurrent run-time of the two HP boilers

Traditionally, the most effective energy performance is obtained via the HP boilers (31-bar) as opposed to the 14-bar small Babcock boilers. The HP boilers further support the maximum power generation by the existing Turbo Alternator (TA) set, which limits the electrical power imports. The typical HP boiler run-time cycle used to be 4 weeks, after which the boiler would be decommissioned, cooled, cleaned and the essential maintenance rendered, prior to returning it to service. In recent times, a 'back to basics' programme was implemented, which involved the detailed process of upskilling the vendors responsible for cleaning and a focused approach to inspections and buy-offs, prior to returning it to service. This detailed and focused approach with key quality inspection gates has seen the boiler run-time cycle increase from 4 weeks to 8 weeks.

Optimisation of 'unburnt coal' in ash

The refinery boilers are designed to combust A-grade coal and the typical unburnt coal fraction in the ash can range from as low as 10% to as high as 20%, depending on the quality of the coal and operational factors. Much focus and attention to detail has recently been deployed in this regard. Some of the key interventions in this aspect are as follows:

- All operational staff have been trained to spot unburnt coal, by using visual sampling methods on the ash belt;
- Shift samples are composited and tested for unburnt coal with a target of <10% set;

- The grate speed and bed heights have been through an extensive trial-and-error approach, to optimise the burn-off and to maintain these key parameters, together with the steady state operations (avoiding stop/starts); and
- Incoming quality monitoring and partnering with the mining suppliers has ensured that A-grade standards are maintained and deviations from key parameters, i.e. volatile and fixed carbon, are addressed timeously.

Broader energy management system implementation

Developing a comprehensive energy management system involves a systematic approach to monitoring, analysing and optimising the energy use throughout the refinery. An Energy Dashboard and reporting system is used to monitor the energy use within the refinery. The key components include real-time monitoring, which uses meters to collect data on energy consumption across the various processes and unit operations. To ensure continuous improvement, corrective actions are implemented, based on the data insights. Future work involves using analytical tools to identify the patterns, inefficiencies and further opportunities for improvement (e.g. the usage of grey water in non-potable areas, as well as repurposing the flue gas and ultrasonic leak detectors).

Future work

The refinery's future work will revolve around the optimisation of the vapour bleeds from the evaporators and condensate systems, in order to maximise the application of hot-water heating within the process and integrating cooling crystallisation into the white boiling systems.

The refinery is in the process of phasing out the 4-bar ribbon calandrias in the white house pans, and it will migrate into a single-range 1.2-bar exhaust, thus simplifying the steam process control logic and maximising power generation. This will also uncouple the refinery's electrical grid from the metro grid, thus enabling an island operation.

Mixed fuel options are also being evaluated and, most recently, woodchips have been blended into the HP boilers; the early results show that a low blend option (<10% woodchips) may be possible. Woodchips exhibit adequate energy properties and a high volatile content, which is therefore favourable for combustion in boilers. Furthermore, woodchips are a renewable energy source and, therefore, they have the potential to reduce the reliance on fossil fuels and subsequently to reduce the environmental impacts. These trials continue to be explored, together with the option of the torrefaction of bagasse from the mills. Possible impacts, such as increased slagging and fouling, will also be investigated.

In the long-term, the strategy of decommissioning the recovery house facility that relies on traditional evaporative crystallisation, in favour of chromatographic techniques, represents a substantial paradigm shift. This transition is anticipated to markedly enhance both the energy efficiency and the product yield.

Conclusion

The energy efficiency initiatives undertaken by the Rossburgh Sugar Refinery demonstrate the tangible benefits of process optimisation and waste heat recovery. By focusing on key areas, such as melter brix optimisation, lime slaking and the recovery of waste heat, the refinery has achieved substantial energy savings. These efforts have not only enhanced its operational efficiency, but they have also contributed to environmental sustainability by reducing fossil fuel consumption and the associated emissions. The strategies that have been implemented serve as a model for other similar areas in the factory that aim to improve their energy efficiency and to ultimately *kill-the-joule*.

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