OPTIMISING IMBIBITION IN A SUGAR MILL WITH COGENERATION

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Abstract

Design of raw sugar factories has traditionally focused on achieving a balance between the energy demand of the factory and the energy contained in the available fuel supply (i.e. bagasse). This has been particularly true in South Africa, where historically low prices have discouraged any investment for the purposes of exporting electrical energy to the national grid. This approach to factory design yields factories with a relatively low capital cost, but often with reasonably poor levels of energy efficiency. However, the current drive towards cogeneration has changed industry thinking in this regard.

Standard sugar industry practice aims at maximising the recovery of sucrose from cane by maximising the amount of imbibition water that is applied to the extraction plant, while remaining within the constraints of the bagasse supply. This is a sensible approach for a factory producing only one valuable product. However, this optimisation method is no longer valid for a cogeneration factory producing a product mix which includes both raw sugar and electrical power. While sugar recovery is maximised by increasing the rate of imbibition, this reduces the potential for electrical power export. The current study demonstrates techniques that can be used to determine the economic optimum for a typical South African raw sugar mill, based on detailed modelling of the extraction plant (e.g. a diffuser) and the energy balance of the factory. The best financial outcome for the mill occurs at an imbibition rate lower than that conventionally applied in the local industry.

Keywords: imbibition, extraction, cogeneration, electricity, energy, optimisation

Introduction

Historically, the South African sugar industry has had a limited demand for the export of energy (or energy-containing products such as bagasse). This has generally taken the form of steam export to by-products facilities or back-end refineries, bagasse export to paper mills or animal feed plants and electrical power export to the national grid. The prices achieved for these energy exports have usually been poor. In particular, the extremely low prices paid for cogenerated electricity in South Africa have discouraged any major investment for the purposes of electrical power export.

The design of raw sugar factories has traditionally focused on achieving a close balance between the energy demand of the factory and the available energy in the incoming cane supply (Schorn *et al.*, 2005). Mills have thus usually been designed to eliminate (or, at least, minimise) any unwanted bagasse surpluses which would create a disposal or incineration problem, as well as to eliminate the need for the consumption of expensive supplementary fuel (Love *et al.*, 1999). This approach yields factories at a relatively low capital cost, but often with reasonably poor levels of energy efficiency.

Even those mills with a market for fibre, steam or power have not targeted extreme levels of energy efficiency. Rather, their design has aimed at allowing sufficient flexibility so that they can achieve a fuel balance over a wide range of operating conditions. For example, the basic design of the Felixton mill allowed for a reasonable level of energy efficiency in order to facilitate the supply of bagasse fibre to a paper mill, without the need for the factory to consume coal as a supplementary fuel (Reid and Rein, 1983). However, this design was also capable of adaptation so as to allow for an increased level of bagasse sales (high energy efficiency), or for the complete cessation of fibre exports (low energy efficiency).

Recent developments within the sugar industry are tending to change the conventional approach to sugar mill design, as described above. The potential of sugar factories to export substantial amounts of renewable energy (particularly in the form of ethanol or of 'green' electrical power) is being recognised. The traditional economic drivers for the industry are changing and this is leading to a desire to achieve much higher levels of energy efficiency, in order to maximise the amount of energy that can be exported. In South Africa, in particular, the market for electrical power is becoming much more attractive (even excluding any renewable energy price premium) because of the shortage of Eskom generating capacity and the sharply increasing power price. The redesign of existing sugar mills in order to carry out the large-scale cogeneration of electricity is thus currently under serious investigation.

Standard operating practice in a sugar mill aims to increase the recovery of sucrose from the cane supply by maximising the amount of imbibition water that is applied to the extraction plant (either diffuser or mills), while remaining within the constraint of the available fuel supply. This is a sensible approach for a factory that produces only one valuable product (raw sugar), and previous work done by Wienese (1994) and by Reid (2006) focused on optimising the economic trade-off between imbibition rate and coal consumption in order to maximise profitability under standard operating conditions in the South African industry. However, these optimisation results are no longer valid when a factory produces a product mix that includes both raw sugar and electrical power. While sugar recovery may be maximised by increasing the rate of imbibition, this reduces the potential for electrical power export.

The objective of the current study is to demonstrate some techniques that can be used to determine the economic optimum imbibition rate for a typical South African sugar mill that has been redesigned for the large scale cogeneration of electrical power. The methods used include the modelling of the extraction process in the diffuser, the detailed modelling of the energy balance of the factory and the modelling of the division of proceeds system in the South African sugar industry. The work described here is similar in principle to that carried out by Wienese (1994) and Reid (2006), as mentioned above. However, the current study is of a more detailed nature and allows for the large-scale export of cogenerated electrical power.

It should also be noted that the previous studies attempted to balance the benefit of applying more imbibition against the cost of burning coal as a supplementary fuel. In the current investigation, there is no consumption of coal under any conditions. Rather, the fuel supply (i.e. the bagasse) is assumed to be fixed and it may be used either to increase sugar production (by increasing the imbibition rate) or to increase electrical power production.

Large scale cogeneration

For demonstration purposes, the sugar mill used as the basis for the current study is the Tongaat Hulett Amatikulu (AK) mill. This factory traditionally sells a small quantity of bagasse fibre for paper production, and exports a small amount of electrical power into the national grid. On this basis, the mill typically achieves a balance with its fuel supply and avoids the generation of sizeable bagasse surpluses, or the need to regularly consume supplementary fuel.

The scope for large scale cogeneration of electricity at AK is currently restricted by constraints relating to installed boiler capacity, turbo-alternator capacity and the inherent level of energy efficiency of the sugar factory itself. These limitations could be overcome in a number of different ways. However, for the purposes of the current study, two particular design alternatives have been investigated in detail. These are referred to as the *high efficiency scenario* and the *low efficiency scenario*. Rather than discussing the specific design alternatives in great detail, this study aims at investigating the particular trade-off between sugar recovery and electrical power export that is available under each of these alternatives. The general methods used to carry out this investigation may be similarly applied to any other sugar mill scenario to determine, as is done here, the optimum imbibition rate to be applied in order to maximise profitability.

General considerations

In both of the alternatives investigated here, the export of bagasse fibre for the production of paper has been stopped, because it is assumed that the fibre would have more value to the sugar mill as a cogeneration fuel. In addition, the design of the mill under cogeneration has been limited in both cases to remain within the constraint of the available bagasse supply. This ensures that all of the electrical energy exported by the mill is renewable in nature. No consumption of supplementary fossil fuel has been allowed for.

In both cases, it was assumed that three of the four existing boilers at AK would be scrapped, due to their age and condition, and replaced with a single new unit. The remaining 85 t/h boiler would be upgraded to improve its efficiency, while increasing its capacity to 100 t/h.

High efficiency scenario

In designing a cogeneration mill for extremely high levels of energy efficiency, use was made of both conventional technology and of more unusual methods of energy saving. This scenario thus incorporates a degree of technical risk, as well as being more capital-intensive (and therefore expensive) than the *low efficiency scenario*. The design employed, as briefly described by Sharma and Peacock (2008), is capable of operating at an efficiency of as low as 38% exhaust steam on cane.

As part of the *high efficiency scenario*, it is proposed that a new 210 t/h 86-bar boiler be installed to replace the three scrapped units at AK. Two new 86-bar turbo-alternators would be installed, namely a 30 MW condensing unit and a 12 MW back-pressure unit. The existing 32-bar back-pressure turbo-alternators, with a total capacity of 12 MW, would be retained for use with the upgraded 100 t/h 32-bar boiler. The other changes to the existing factory configuration may be summarised as follows:

- Diffuser heating would be converted from V1 vapour to V2 vapour (both for use in the scalding juice heaters and for direct injection heating of the diffuser).
- The draft juice temperature exiting the diffuser would be decreased from its current average value of 65ºC to around 55ºC, by reducing the performance of the scalding juice

heaters. The reduced draft juice temperature will facilitate the use of low-grade bleed vapours for mixed juice heating (Munsamy, 2008). Direct steam injection with V2 vapour into the second stage of the diffuser can be used to compensate for the reduced level of heating being carried out in the draft juice stage.

- Direct-contact heating of the diffuser press water with V3 vapour would be required (Singh and Allwright, 2000).
- Mixed juice heating at AK is currently carried out using both V2 vapour and V1 vapour, in seven shell and tube heat exchangers. To maximise energy efficiency, the installation of seven new heaters would be required, which would allow for four-stage mixed juice heating using V4, V3, V2 and V1 vapours.
- Clear juice heating is currently carried out at AK using both V1 vapour and exhaust steam. For energy efficiency reasons, it is proposed that all heaters be converted to operate using V1 vapour alone.
- All pans are converted from V1 vapour to V2 vapour operation. This may require the installation of pan stirrers in the batch pans, so as to ensure adequate massecuite circulation. Alternatively, some of the existing batch pans could be converted into continuous pans of the new Tongaat Hulett circular design, as continuous pans are less sensitive to lower vapour supply pressures.

A particular feature of the *high efficiency scenario* factory design is the quadruple effect evaporator station configuration, which was discussed and modelled by Sharma and Peacock (2008). The final effect vessels of this arrangement are operated at an elevated pressure of 35 kPa(a), thereby raising the pressure profile of the entire station and allowing for more effective use of the low grade bleed vapours for heating purposes. The juice leaving the fourth effect vessels (at a brix of about 64%) is then flash-cooled to a pressure of 15 kPa(a) in a separate flash cooler, which brings the final syrup brix to above 65% while also producing a low-temperature syrup feedstock for the pan floor.

The 35 kPa(a) pressure of the V4 bleed stream from the evaporator station (equivalent to a saturated vapour temperature of 72.7°C) allows it to be used to heat the mixed juice stream exiting the extraction plant. Under the season-average crushing conditions studied by Sharma and Peacock (2008), the quantity of V4 bleed vapour available from the evaporator station was almost exactly balanced against the quantity of V4 bleed vapour required for this heating duty. The design of the factory is also such that the entire amount of water available for evaporation from the clear juice stream (in order to produce syrup) is almost exactly equal to all of the bleed stream requirements of the evaporator station. There is thus no need to condense any ‘excess’ V4 vapour in a condenser, or to supplement the supply of available V4 vapour by means of exhaust steam letdown. However, it is obviously unlikely that the mill will operate continuously under these season-average conditions over the entire duration of the crushing period. For the conditions employed in their study, which are slightly different to those employed here, Sharma and Peacock (2008) showed that exhaust letdown into the V4 range would be required for up to 60% of the time, while for the remaining 40% of the time there would be an excess of V4 vapour available. The use of exhaust steam letdown into the evaporator station during periods of V4 vapour shortage obviously reduces the energy efficiency of the factory[1].

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[1] Because all of the ‘excess’ water in the clear juice stream is already being used to produce bleed vapour in the evaporator station, there is no way to increase the availability of V4 vapour other than by means of an exhaust steam letdown.

Depending on the operating parameters of the factory (particularly the imbibition rate applied to the diffuser), the *high efficiency scenario* is capable of producing between 24.0 and 25.8 MW of electrical power on average, for export to the national grid.

Low efficiency scenario

In designing a lower efficiency cogeneration mill option, use was made of conventional technology only for energy saving. This scenario thus incorporates very little technical risk, and is cheaper than the *high efficiency scenario*. The design employed is capable of operating at an efficiency of around 41% exhaust steam on cane.

As part of the *low efficiency scenario*, it is proposed that a new 190 t/h 32-bar boiler be installed to replace the three scrapped units at AK. Two new turbo-alternators would be installed, namely a 20 MW condensing unit and a 10 MW back-pressure unit to work in parallel with the existing 12 MW back-pressure turbo-alternator capacity. The one remaining existing boiler would be upgraded from 85 t/h to 100 t/h. The other changes to the existing factory configuration may be summarised as follows:

- Diffuser heating would be converted from V1 vapour to V2 vapour (both for use in the scalding juice heaters and for direct injection heating of the diffuser).
- Direct-contact heating of the diffuser press water with V3 vapour would be required (Singh and Allwright, 2000).
- Mixed juice heating at AK is currently carried out using both V2 vapour and V1 vapour, in seven shell and tube heat exchangers. To improve energy efficiency, the installation of three new heaters would be required, which would allow for three-stage mixed juice heating using V3, V2 and V1 vapours.
- Clear juice heating is currently carried out at AK using both V1 vapour and exhaust steam. For energy efficiency reasons, it is proposed that all heaters be converted to operate using V1 vapour alone.
- The existing quadruple effect evaporator station is converted to a conventional quintuple effect with the installation of two new Kestners as parallel first effect vessels.
- All pans are converted from V1 vapour to V2 vapour operation. This may require the installation of pan stirrers in the batch pans, so as to ensure adequate massecuite circulation. Alternatively, some of the existing batch pans could be converted into continuous pans of the new Tongaat Hulett circular design, as continuous pans are less sensitive to lower vapour supply pressures.

Depending on the operating parameters of the factory (particularly the imbibition rate applied to the diffuser), the *low efficiency scenario* is capable of producing between 17.8 and 19.2 MW of electrical power on average, for export into the national grid.

Imbibition optimisation

In order to maximise the amount of electrical power produced by cogeneration in a sugar mill it is necessary to install a condensing turbo-alternator, as these recover more energy from each ton of steam than is possible with back-pressure turbo-alternators. For example, using high pressure steam at 86 bar(a) and 520°C, a condensing turbo-alternator would typically require as little as 3.6 tons of steam per MWh of electrical power generated, while a back-pressure turbo-alternator would consume approximately 5.1 tons of steam per MWh under the same conditions. The disadvantage of the condensing unit is that it does not produce any exhaust steam for subsequent use in sugar processing. This results in direct competition for high pressure steam between the sugar mill and the cogeneration facility, which needs to be effectively managed in order to maximise the profitability of the entire enterprise.

Typically, sugar mills aim to increase the recovery of sucrose in their extraction plant by maximising the amount of imbibition water that is applied to the cane, within the constraint of the available fuel supply. This is a sensible approach when the only objective of the factory is to maximise the production of a single raw sugar product. However, increasing the amount of applied imbibition results in an increased steam demand of the sugar processing portion of the plant (particularly in, but not limited to, the evaporator station). For a large-scale cogeneration factory, this means that less high pressure steam is available for the generation of electricity using a condensing turbo-alternator. Instead, a greater quantity of the available high pressure steam must pass through the less effective back-pressure turbo-alternator/s in order to meet the increased mill demand for exhaust steam. Increased imbibition therefore leads directly to a loss in potential electricity sales. By contrast, the amount of cogenerated electrical power could be maximised by limiting the amount of imbibition applied to the diffuser or milling tandem. This would make a greater quantity of high pressure steam available for use in a condensing turbo-alternator, but would reduce the sugar recovery achieved.

To ensure that the facility as a whole achieves maximum profitability, it is necessary to optimise the amount of imbibition water applied to the extraction plant. A balanced trade-off needs to be achieved between the sugar revenue and the earnings from the sale of electrical power. The optimum rate of imbibition will obviously be a function of the sales prices achieved for both raw sugar and electrical power. The optimum imbibition will also be a function of the particular factory configuration considered. It is not advisable to extrapolate the results obtained in a study such as this one to other sugar mills. The techniques demonstrated here should rather be used to carry out similar optimisation studies on a case-by-case basis.

Results

To model the effect of changing imbibition on the performance of the factory, a relationship between imbibition and diffuser extraction was required. Using five-year average mill data, the Tongaat Hulett diffuser design model (developed following the work of Rein (1974)) was used to obtain a relationship between extraction and imbibition rates. The five-year data shows that the mill has historically operated within a fairly narrow band of imbibition values, the lowest being 326% on fibre, with an average of 372%. Therefore the reliability of the model cannot be checked over a large range of actual data points. In particular, there is no data at all for low imbibition rates, which is an area of interest in this study. Thus, although the model has been used to extrapolate to imbibition rates as low as 250% on fibre, the accuracy of the results at this end of the range is unproven.

A full steam balance model was set up for both of the operating scenarios (i.e. high and low efficiency) using five-year average data, and the diffuser model relationship between extraction and imbibition was incorporated into this.

By varying imbibition levels between the five-year average figure of 372% and 250% on fibre, the impact on the factory was assessed and the effect on relative quantities of products (i.e. sugar, molasses and electrical power) could be noted. The optimum operating point was then determined as that imbibition rate at which the combined financial benefit of sugar, molasses and power sales is maximised. This point is dependent on the relative selling prices obtainable for each of these products. For sugar and molasses, the price has been calculated through modelling of the South African division of proceeds system. For export power, the price that can be obtained will depend on the details of any sales contracts entered into, but will be at least equal to the current price at which power at the mill is purchased from Eskom. The calculations have thus been repeated for various possible power prices to see the effect that this variable has on the optimum operating point.

Low efficiency scenario

The results obtained while optimising the *low efficiency scenario* at an electrical power sales price of 60 cents per kWh are shown in Figure 1. The graph shows the change in the value of the revenue streams (relative to the current average conditions at 372% imbibition on fibre) for export power, sugar and molasses. The optimum at this power price can be seen to be at an imbibition level of between 300% and 310% on fibre.

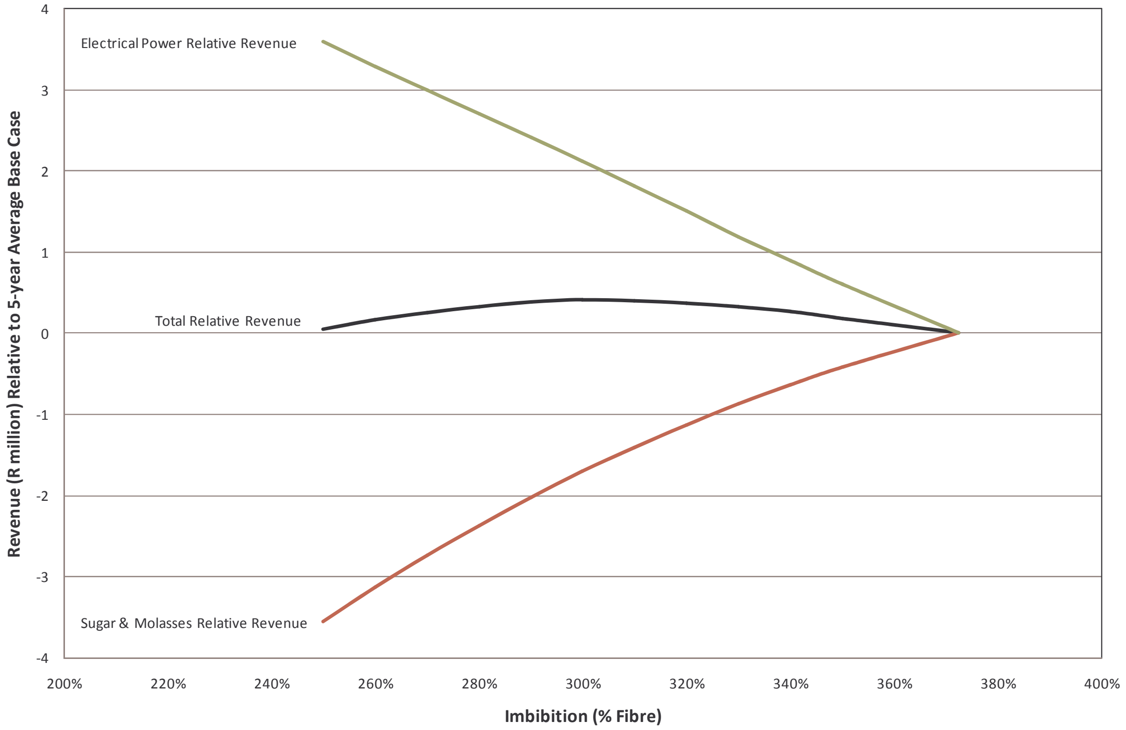

Figure 1. Optimisation of the relative revenue streams at a power price of 60 cents per kWh (*low efficiency scenario*).

For the *low efficiency scenario*, as the price obtained for exported power increases, the optimal imbibition level decreases. This is shown in Figure 2, where the overall financial impact of a changing imbibition rate is shown at a number of different power price levels (relative to the current average conditions at 372% imbibition on fibre). Above a power price of 80 cents per kWh, the maximum point of the revenue curve lies beyond the range under investigation (i.e. at an imbibition rate of less than 250% on fibre). The model validity at such low imbibition levels is questionable and no attempt has therefore been made to extend the modelling work beyond this point. For power prices of less than 40 cents per kWh, there is no financial benefit in reducing imbibition and it would be economically beneficial to run the factory at a higher imbibition level and reduce the power export in favour of more sugar production. As expected, at higher power costs, the value of the export power increasingly outweighs the value of the sugar products lost due to the lower extraction obtained, and it is beneficial to sacrifice some sugar production in favour of increased power export.

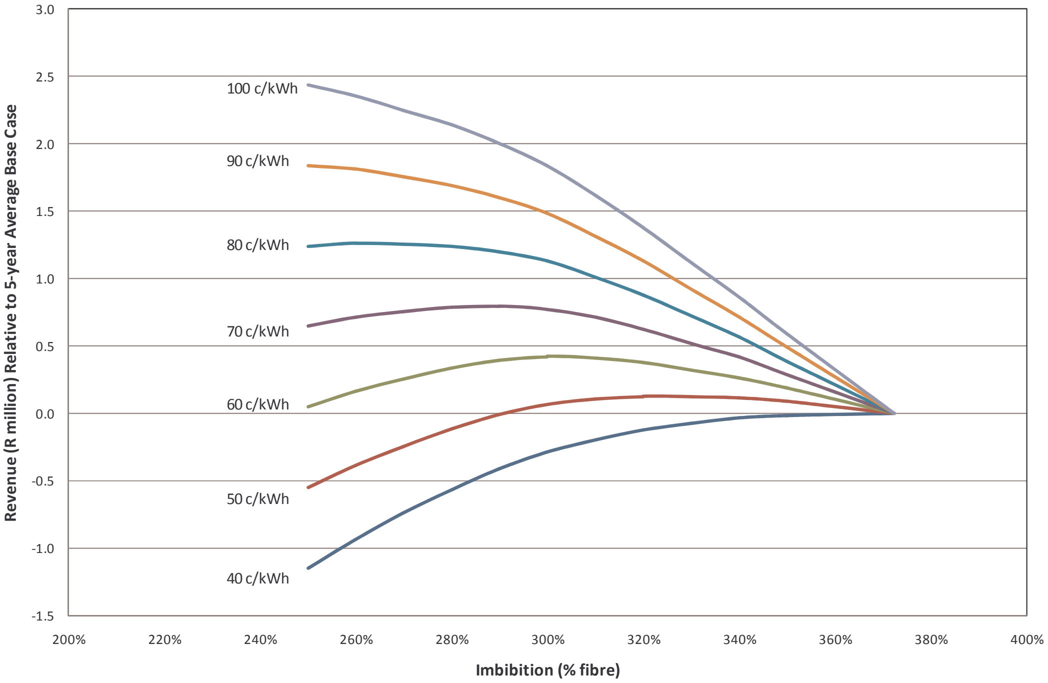

Figure 2. Effect of imbibition rate and power price on overall relative revenue (*low efficiency scenario*).

Figure 3 summarises the optimal point data presented in Figure 2. The graph shows the financial advantage of reducing imbibition rates, when compared to the five-year average case, and also shows how optimal imbibition levels decrease with an increasing power price.

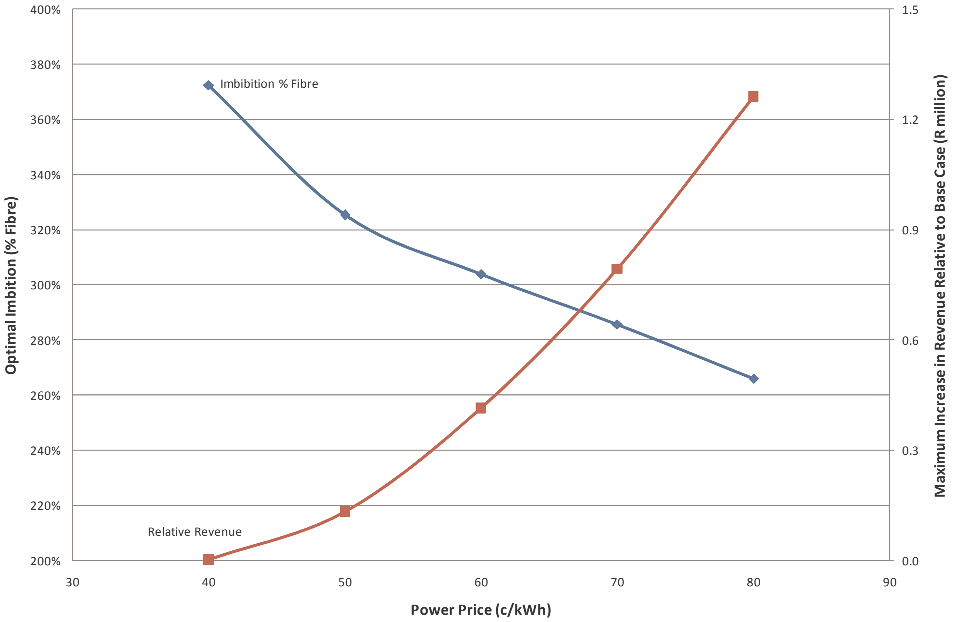

Figure 3. Effect of power price on optimal imbibition and relative revenue (*low efficiency scenario*).

High Efficiency Scenario

The results obtained in optimising the *high efficiency scenario* at an electrical power sales price of 60 cents per kWh are shown in Figure 4. The graph shows the change in the value of the revenue streams (relative to the current average conditions at 372% imbibition on fibre) for export power, sugar and molasses. The optimum at this power price (and, indeed, at all power prices studied for this scenario) can be seen to be at an imbibition level of 310% on fibre.

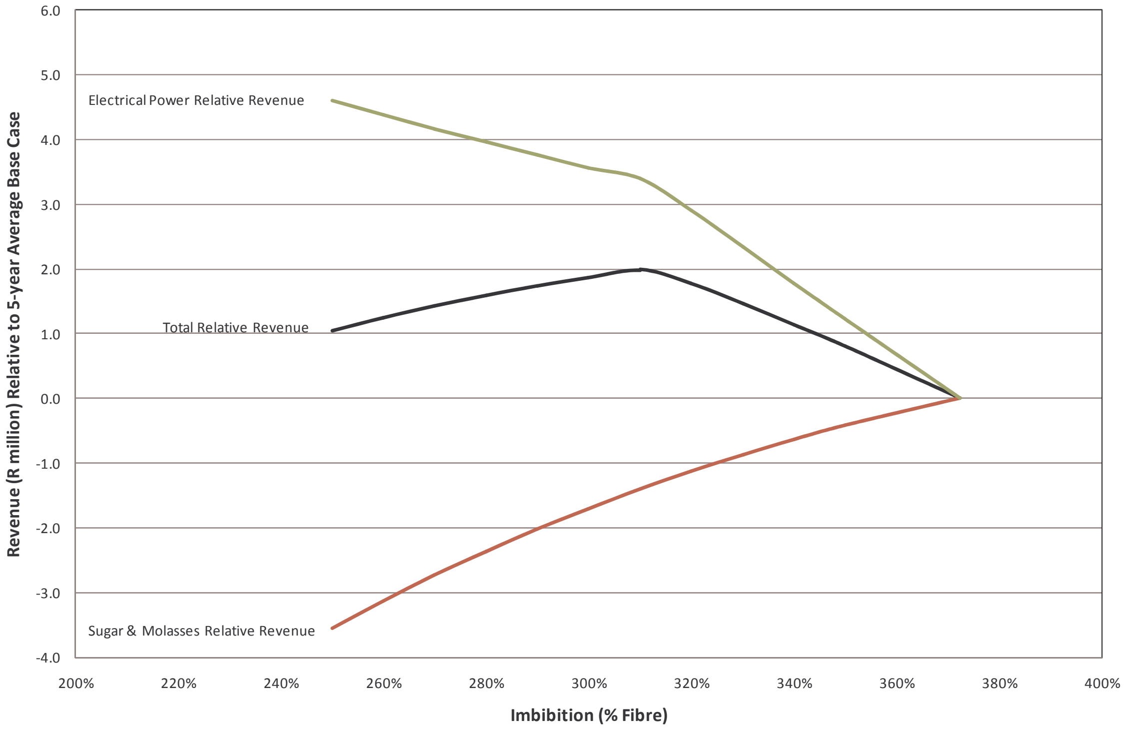

Figure 4. Optimisation of the relative revenue streams at a power price of 60 cents per kWh (*high efficiency scenario*).

For all power prices considered in this case, which ranged from 40 cents per kWh to 100 cents per kWh, the maximum revenue as compared to the five-year average occurred at an imbibition of 310% on fibre. These results were somewhat unexpected, and differed from the *low efficiency scenario*, where the optimal imbibition rate to maximise revenue depended on the power cost. In Figure 5, the overall financial impact of a changing imbibition rate is shown at a number of different power price levels (relative to the current average conditions at 372% imbibition on fibre). The effect of reducing imbibition rates and the change in power price on the overall relative revenue earned by the mill can be clearly seen.

The reason for the major difference between the *high* and *low efficiency scenarios* is the fact that at 300% imbibition, all of the V4 vapour produced in the evaporator station is fully utilised for mixed juice heating. At lower imbibitions, there is no more water available for evaporation from the clear juice to produce bleed vapours in the evaporator station, and as a result the heating duty of the factory must be partially met by exhaust steam let-down. This rapidly reduces energy efficiency, making it less economically attractive to operate at imbibition rates lower than 300% for the *high efficiency scenario*.

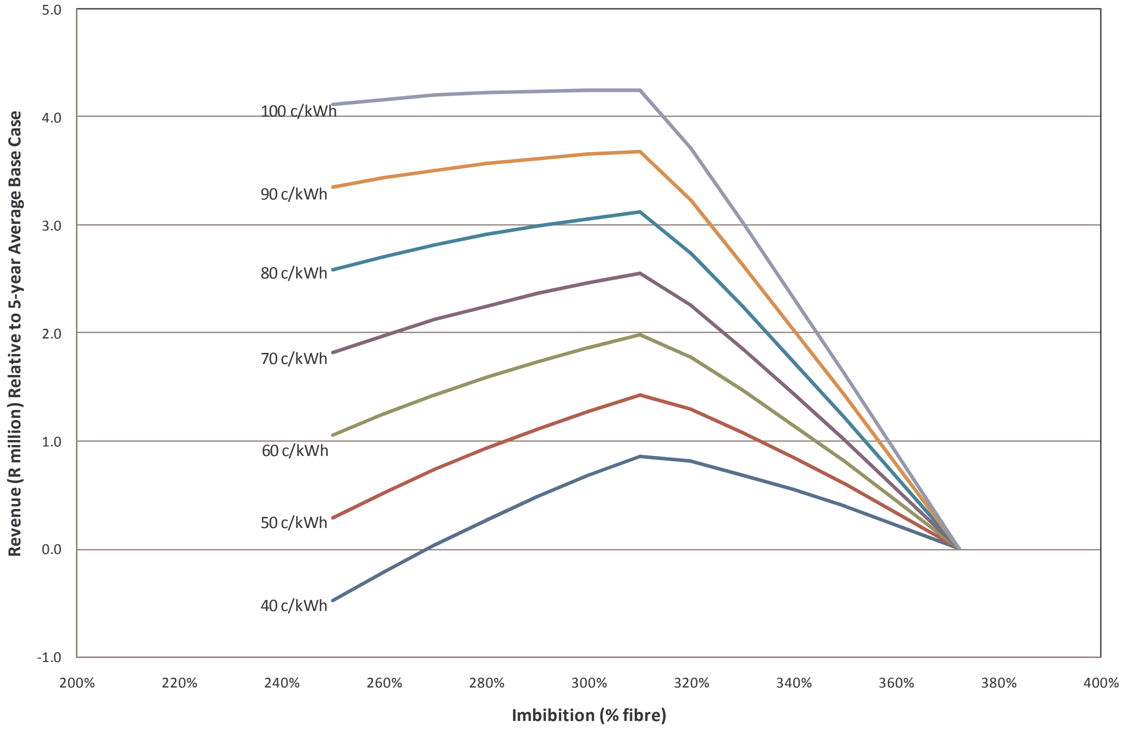

Figure 5. Effect of imbibition rate and power price on overall relative revenue (*high efficiency scenario*).

Conclusions

Recent developments within the sugar industry are tending to change the conventional approach to sugar mill design. The potential of sugar factories to export substantial amounts of renewable energy is being recognised. The redesign of existing sugar mills to carry out large-scale cogeneration of electricity is thus currently under serious investigation and the objective of the current study is to demonstrate some techniques that can be used to determine the economic optimum imbibition rate for a mill such as AK.

Analysing the effect of imbibition on sugar recovery and power export, an optimum value of imbibition was found whereby revenue was maximised. For the *low efficiency scenario*, an increase in the price of electrical power will reduce the optimal imbibition level, as expected. However, in the *high efficiency scenario*, no change in optimal imbibition rate with power price was found. This is due to the particular nature of this highly efficient factory design which loses energy efficiency below a fixed imbibition rate.

The optimal imbibition rate, particularly at high power prices, is substantially below those levels normally employed in the South African sugar industry. The optimum level was also found to be far below that obtained in the work of Wienese (1994) and Reid (2006). However, this can partially be explained by the fact that these studies did not consider the large-scale export of cogenerated electrical power, which would tend to decrease the optimum rate of imbibition. The relative values of sugar, molasses and coal have also changed markedly since these previous studies were carried out. For example, while the average sugar and molasses prices in the South African industry have approximately doubled since the work of Wienese (1994), the price of coal has increased more than sixfold. This change in relative value will tend to decrease the optimum imbibition rate for the situation in which coal consumption is being traded off against imbibition.

The lack of factory data in the low imbibition operating range means that the reliability of the model outputs under these conditions is uncertain. One of the Tongaat Hulett mills is therefore currently embarking on full scale trials at low imbibition levels to gather more operating data in this region.

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