REFEREED PAPER

FACTORY ENERGY OPTIMISATION POTENTIALS

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Introduction

Energy saving has so far been of little interest for South African sugar mills. From an environmental point of view this is a drawback, as cane sugar factories are generally CO_2 neutral, allowing environmentally friendly power export. Looking at the global warming trends the sugar industry can be a forerunner of CO_2 neutral power production at reasonable power production cost. This is of a course a political issue which can't be resolved by the sugar mills on their own.

Modern cane sugar factories allow a power export in the range of 100-145 kWh/t cane (Morgenroth and Batstone, 2005; Batstone and Morgenroth, 2013, Morgenroth and Batstone, 2013). For a 10 000 tcd factory the power export potential is therefore 42-60 MW during the cane season. By storing bagasse, power export can be performed around the year at lower power output levels. Bagasse-based power supply to the national grid is already common practise for some mills in countries like Brazil, India and Pakistan.

As almost all mills in southern Africa burn coal or wood in addition to bagasse because of steam inefficient processes, there is a considerably high cost saving potential. The coal cost amounts to ~1150 ZAR/t or 70 Euro/t. The annual coal demand of South African mills varies substantially and can exceed 70 000 t coal/year per mill (58 Million ZAR or 3,5 Million Euro) while almost all mills employ at least some coal (personal communication at ISSCT Workshop 2014; Madho *et al.*, 2017). The SA industry, as a whole, burns over 200 000 tons of coal-equivalent supplementary fuels per annum. This offers good opportunities for fast paybacks by steam and power saving measures.

Review of energy saving design considerations

Steam savings

There are a wide range of technologies available for performing steam saving measures. Steam saving is usually achieved by a proper mix of equipment, process schemes and automation. The most steam efficient sugar mills can be found nowadays in India and Pakistan with steam on cane levels of 26% (raw sugar factories) and 34-36 % for backend refinery factories. There is still scope for further improvement when looking to the beet sugar industry with a steam demand between 18-22 % steam on beet for central European factories producing directly white sugar (Lorenz, 2010; Morgenroth *et al.*, 1996; Morgenroth *et al.*, 1998; Morgenroth, 2015). Beet sugar factories depend on fossil fuel as energy source. In 1960 many beet sugar factories also showed steam on beet values of ~50% steam on beet. Caused by the oil crisis, beet sugar factories had to reduce their fuel consumptions drastically to ~30%

steam on beet in the 1980's and did proceed down to levels of ~16% on beet in some factories (Austmeyer *et al*., 1995, Niepoth, 2005). Many of the technologies and operational concepts employed to achieve these results can be transferred to the cane sugar industry, which has been partially done, especially in the last two decades.

Minimum steam consumption targets

Some important steam saving measures are:

Mass and energy balances as a prerequisite to determine process inefficiencies
Cold raw juice (diffusers)
Direct contact heaters
Falling film evaporators
Multiple effect bleeding
Operation at increased last vapour pressure from the last evaporation effect
Pan automation
Molasses conditioners.

Southern African sugar mills show steam usages between 40-75% steam on cane depending on the sugar quality produced (personal communication, 2014-2019).

Impact of evaporator technology

Robert and Kestner evaporators allow steam saving only down to a level of 36-40% steam on cane. Below this level, falling film tubular or falling film plate evaporators are at least partially essential. Experience has been gained with falling film evaporators in the last decades (Austmeyer *et al*., 1996, Avram *et al.,* 2007, Grant *et al*., 2001, Journet, 2005, Morgenroth, 2002; Walthew *et al.*, 1997). Nowadays the leading evaporator type in the beet sugar industry, the falling film plate technology, has been developed to a large extent at the Gledhow sugar factory in a co-operative project between Gledhow, the SMRI, the Berlin Sugar Institute (Technical University of Berlin, Germany) and the evaporator manufacturer Balcke-Duerr, Germany (Walthew *et al.*, 1997).

The benefit of falling film evaporators is that they require a smaller delta T than rising film evaporators. Figure 1 displays typical heat transfer coefficients, usually referred to as k-values (W/m^2K) of different evaporator types. The k-value describes the rate of heat transfer achieved per unit surface area and per unit temperature difference. However, in the case of rising film evaporators (Robert, Kestner and rising film plate type) the k-values depend on the specific heat flow densities (kW/m^2) as displayed in Figure 2. Rising film evaporators only perform well in case of heat flow densities between 12-25 kW/m^2 corresponding to larger delta Ts.

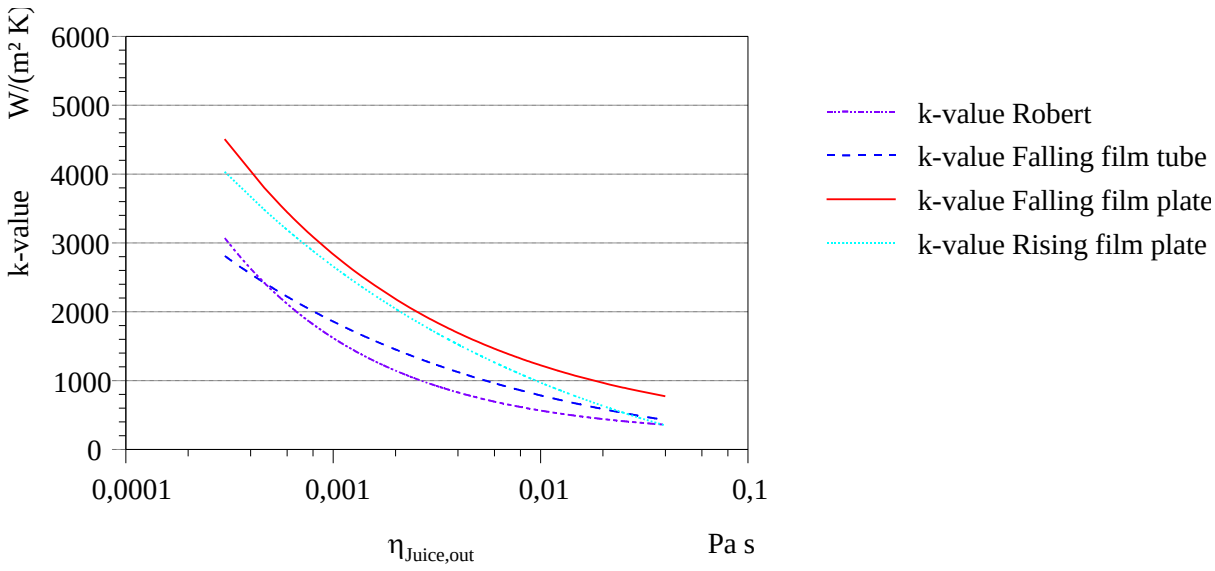

Figure 1. Evaporator performance (k-value) for different viscosities and evaporator types (Morgenroth, 2002).

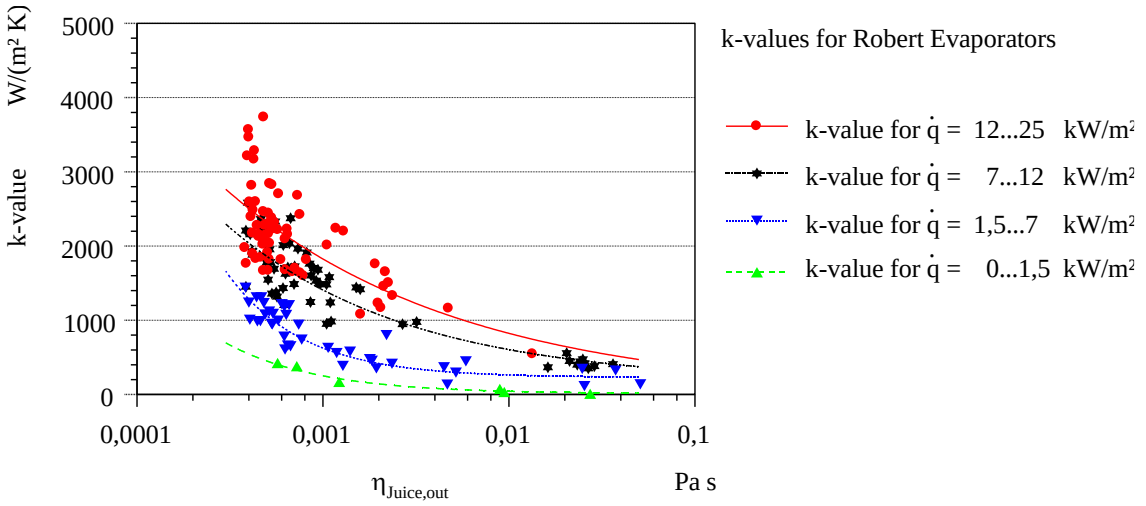

Figure 2. Influence of the specific heat flow density on the evaporator performance (k-value) (Morgenroth, 2002).

The available delta T of a multi-effect evaporation station ranges from ~120 to 54°C for a typical cane sugar factory. Thus, a 66 K temperature drop is available. Robert and Kestner evaporators require, depending on the effect, between 5-30 K delta T per effect. If the temperature difference is reduced to 120-88°C, only 32 K total temperature difference is available, and the delta T shrinks to 6,4 K per effect. In the first and second effect this is still sufficient to operate Robert and Kestner evaporators, but in the later effects the k-value of these evaporator types will be affected as displayed in Figure 2. However, because of easier tube cleaning, falling film evaporators are often employed first in the effects 1-2, whereas they are more efficient in the later effects. Increasing the vapour temperature of the last effects allows bleeding to the pan station from the 3rd and 4th effects and also to employ more vapour 4 and vapour 5 for juice heating.

The first complete falling film tubular evaporation plants based on IPROs design have been commissioned in India (at Shree Renuka, Athani factory in 2007), in Pakistan (at AlMoiz in 2007) and Brazil (at Zilor, Quatá factory in 2008; falling film plate) and are operated with very high steam efficiency. Since this time, a boom of installations of falling film evaporators

followed, with nowadays a couple of hundred installations worldwide estimated by the authors. A five effect falling film evaporation plant is shown in Figure 3.

Figure 3. Five effect falling film evaporation train in AlMoiz, Pakistan.

Modern vapour bleeding schemes

Figure 4 shows the vapour bleeding scheme of a modern, high efficiency falling film tubular evaporation plant achieving a very low exhaust steam demand of 31,7% steam on cane. The main features are:

1. Falling film technology with small delta Ts especially in the 3-5 effect. This is the major difference between Robert and falling film evaporators. Only falling film evaporators allow operation with good performance at small temperature differences while Robert evaporators cannot perform in this situation. Please refer also to Figure 2 displaying the impact of the heat flow density (or in other words the temperature difference) on the thermal performance (k-value) of Robert evaporators. Also, the heating surface required and therefore the investment cost is increased in case of employing Roberts evaporators in the proposed evaporator scheme.
2. Vapor bleeding from every effect. This allows minimising the vapour loss to the condenser as one major source of steam loss and therefore a reduction of steam demand. Roughly, the exhaust steam demand in t/h or percent steam on cane equals the amount of vapour sent to the vapour consumers minus the flash vapour recovered from stepwise condensate flashing which has also been considered here.
3. Pan operation using 3rd and 4th vapour instead of exhaust or vapour 1-2 as typically done in many South African sugar factories. This allows using the multiple evaporation effect of the vapour extracted at a later effect and therefore reduces the steam consumption of the plant.
4. Increased vapor temperature of the 5th evaporator effect at ~88°C. The benefit of the elevated vapour temperature of the last effect is to use more final effect vapour for juice heating purposes and to reduce the vapour loss to the condenser.

Pan automation

It should be considered that the largest amount of the steam consumed in a sugar plant is employed at the pan station. Thus, the pan station has a major impact on the plant's energy efficiency and should be a key focus for energy saving measures. For manual operation of a batch pan, usually 2-5 t water per strike are required which leads typically to an additional exhaust steam demand of 2 to 16% on cane for the raw house pans and in addition for the refinery pans (Morgenroth *et al.*, 2013). Supersaturation is the driving force for crystallisation but especially when the labile zone is reached, fines will form spontaneously, spoiling the quality of the massecuite strike. One main task of pan automation is to keep the supersaturation of the mother liquor in the metastable zone preventing formation of fines.

Automated pan management systems allow reducing the water consumption which is usually required to reduce the formation of fine sugar crystals to almost zero. By reducing the amount of water added to the pan, the energy required for the subsequent evaporation is reduced significantly. If exhaust steam is employed for pan operation ±1 ton of water addition requires one ton of additional exhaust steam. In case vapours are used for pan boiling, this factor decreases but still causes an additional exhaust steam demand.

A survey of pan operation has been carried out by Morgenroth *et al.* (2013) for sugar factories in various countries (Brazil, India and Pakistan). Figure 5 displays the amount of steam required for the raw house pans, raw house pans with a back-end refinery and in the refinery section. Figure 5 shows that the practical steam demand is 2 to 4 times higher than the theoretical demand. This shows very clearly how inefficiently many plants are operated. It needs to be mentioned as well that the required additional evaporation reduces the available pan capacity considerably. For all the plants taken into consideration for the comparison, mass and energy balances have been prepared allowing the impact of water addition to the pans to be quantified and also the reduction to zero in the benchmark case. Almost zero water addition is common in the beet sugar industry where energy is costly as fossil fuels are required. Otherwise steam demands in the range of 18-22% steam on beet cannot be achieved. However, apart from proper automation and good operators, good pan designs as well as efficient condensers are required and the feed solution (e.g. A and B molasses) needs to be free of fine crystals avoiding formation of too small crystals in the product pans. Pan stations automated by the authors in the cane sugar industry in the last two decades achieve water reduction levels to the pans between 80 to almost 100%.

Figure 6 displays the corresponding water additions in % on cane. Every ton of water requires to be evaporated and therefore causes additional exhaust steam demand. The benchmark considers zero water addition for automated pans. (The factories with back-end refineries employ 100% of their own raw sugar produced, not considering additional raw sugar from outside sources.)

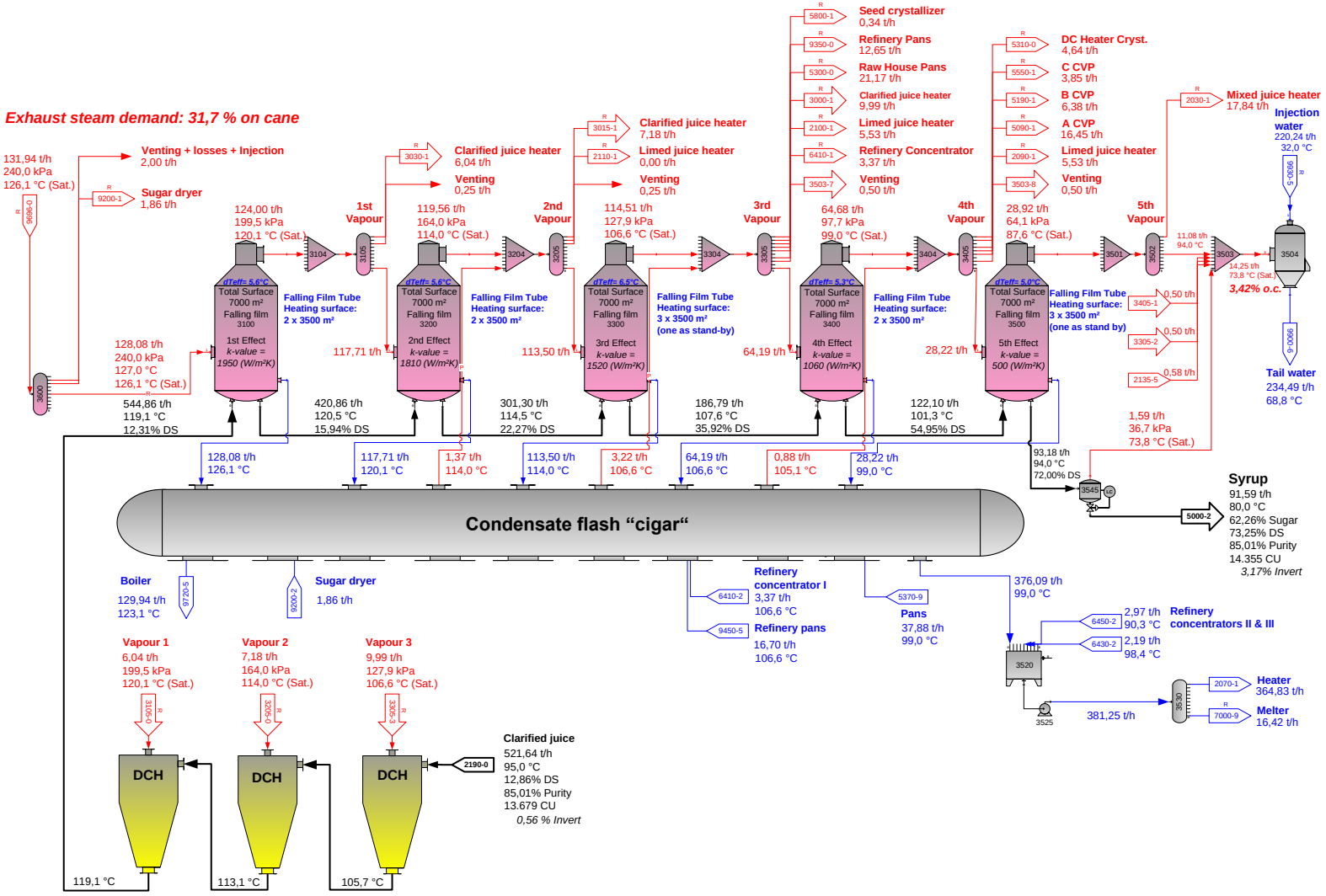

Figure 4. High steam efficient evaporation plant (Morgenroth and Pfau, 2010).

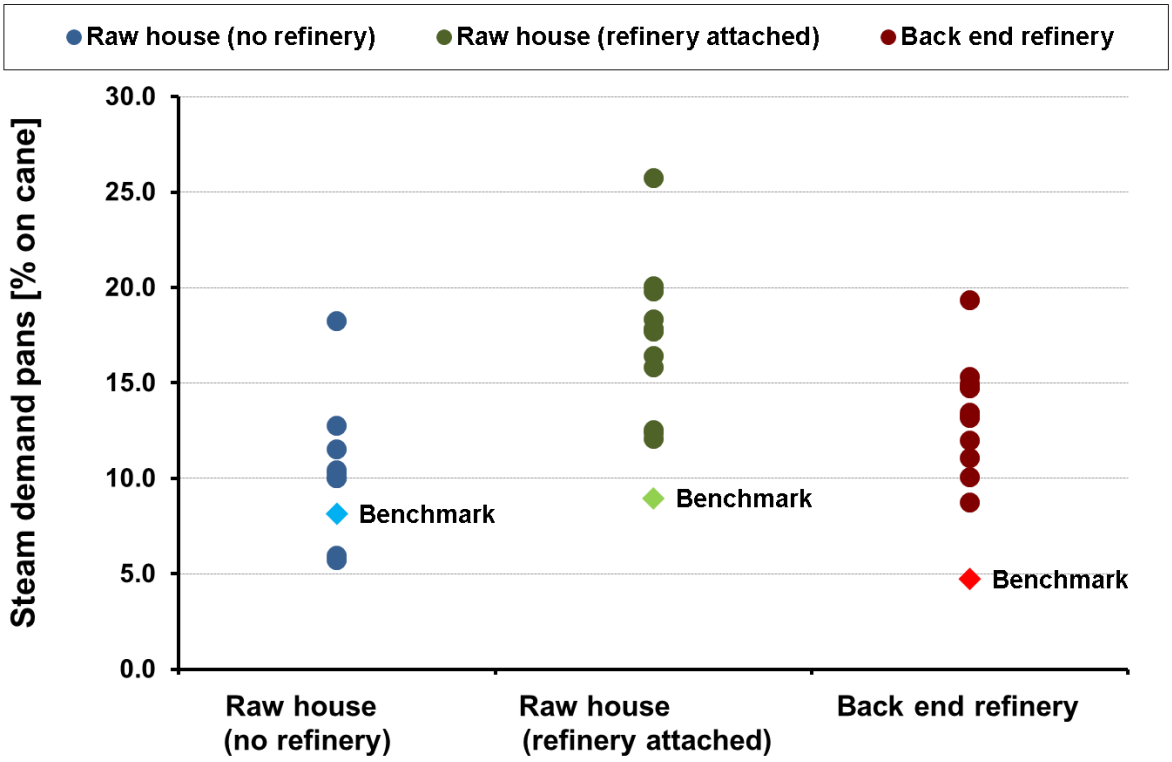

Figure 5. Steam demand of raw and refinery pans (per t cane).

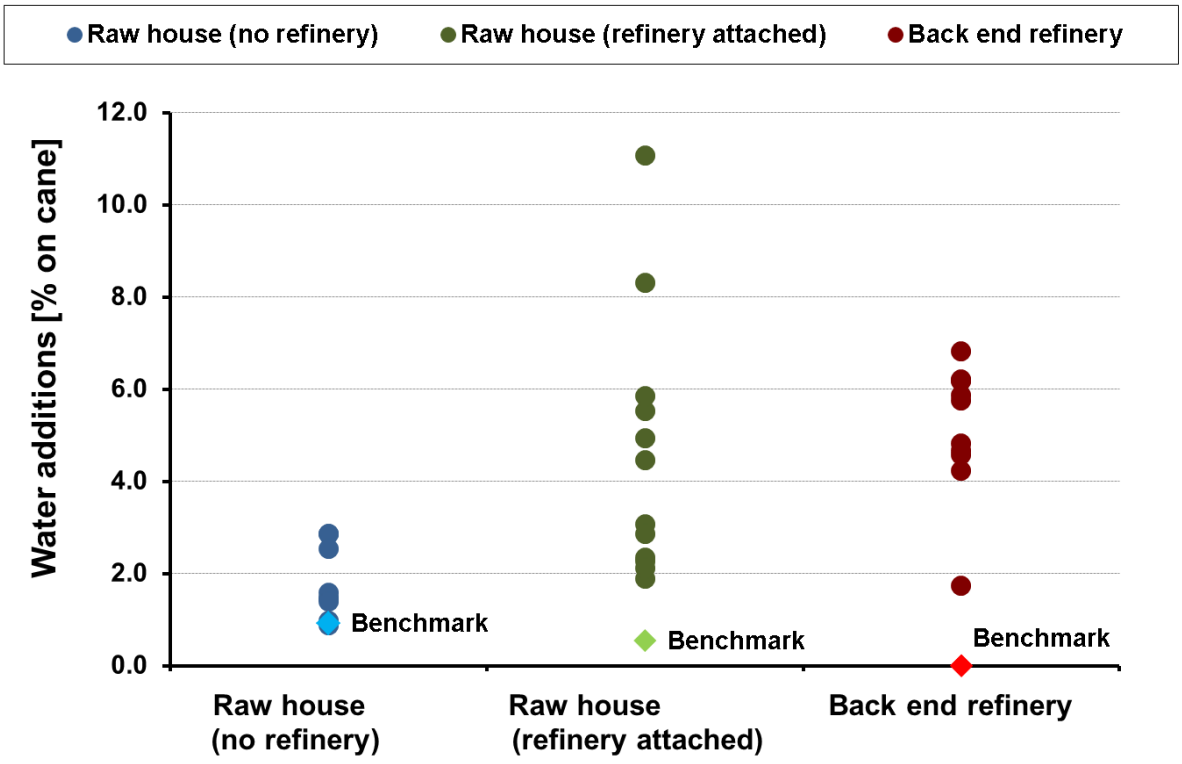

Figure 6. Water addition to raw and refinery pans.

Figure 7 illustrates the basic control loops that are required for the full automation of a batch pan (Morgenroth *et al*., 2013). Obviously, continuous pans also require adequate controls and can operate without any water addition.

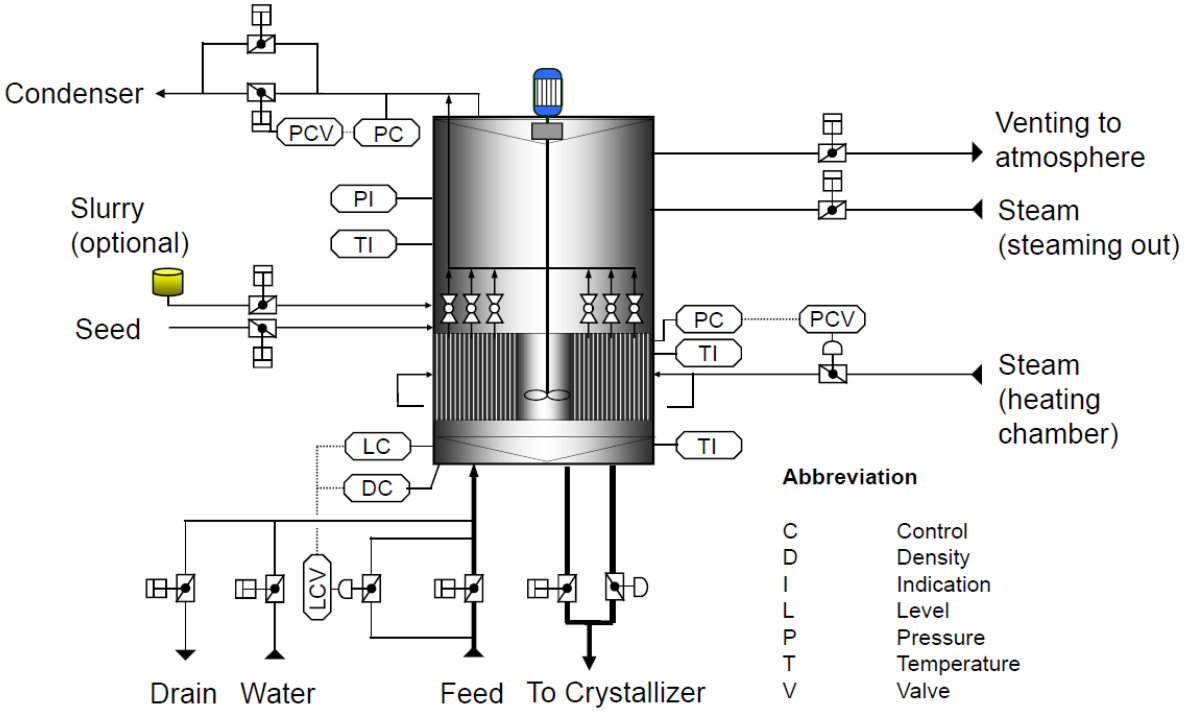

Figure 7. Basic control loops of a batch pan.

A very important aspect for the successful implementation of a pan automation system is the training of operators, process and laboratory team members and the automation technicians in the factory.

Power savings

The drawback of low pressure boilers (22-32 bar) in regard to steam saving is, that at a certain point of process steam efficiency, no make-up steam is required anymore. Thus, further process steam saving is not possible, as that would mean that insufficient power will be produced in the power station to satisfy the factories' power demand (Reid and Rein, 1983). Any further reduction in process steam demand would lead to exhaust steam being vented to atmosphere. This balance point between steam and power demand is usually reached at a process steam demand between 36-44% steam on cane depending on boiler pressure. An important aspect in this regard is the isentropic efficiency of the mill turbine drives which varies according to the experience of the authors often between 32-55% or specific steam consumptions between 11-19 kg/kWh (at 31,5 bara live steam pressure and 400°C live steam temperature). Rein (2017) states typical specific steam consumption levels between 6-15 kg/kWh but this depends of course on the live steam pressure and temperature and the turbine efficiency. The mill drives are often single stage turbines. The isentropic efficiency of multi-stage backpressure turbines varies (in the experience of the authors) between 55-75%. The low isentropic turbine efficiencies of the former type limit the steam saving potential, since the low efficiency turbines generate much greater exhaust steam for the same mechanical power production. Mill electrification can reduce the amount of exhaust steam generated, since the power for the mill electric drives will be generated by more efficient multi-stage turbines in the power station. In such a case, less steam will be generated for process use

(thus allowing for additional process energy-efficient measures); conversely, more steam will be available for power export, e.g. extraction/condensing turbines produce power more efficiently compared to backpressure turbines.

Minimum power consumption targets

The typical power demand for a highly power-efficient sugar factory varies in the experience of the authors between 12-14 kWh/t cane in case of turbine-driven mill drives or between 26-28 kWh/t cane in case of electrified mill drives (Morgenroth and Pfau, 2010). Diffusers reduce the power demand in comparison to mills to ±50 % at the extraction unit (Mullapudi, 2006; Rein, 1995).

Power saving by VFD installation

The installation of VFDs (Variable Frequency Drives) allows reduction of the electrical power demand by slowing the rotational speed of prime movers, as opposed to throttling their output. A similar effect can be found in case of many fans and pump motors where loads fluctuate. However, VFDs for power saving are economically beneficial only for larger motors of above 100 kW as this offers usually a better return on investment compared to smaller motors. Thus, mill drives, boiler fans and pumps with high power demand, i.e. injection water pumps, boiler feed water pumps, mixed juice pumps are beneficial for VFD installations.

Power saving by modern condensers

Another field of power saving are the direct contact condensers. Figures 8 and 9 display various types of jet condensers and other typical types of condensers.

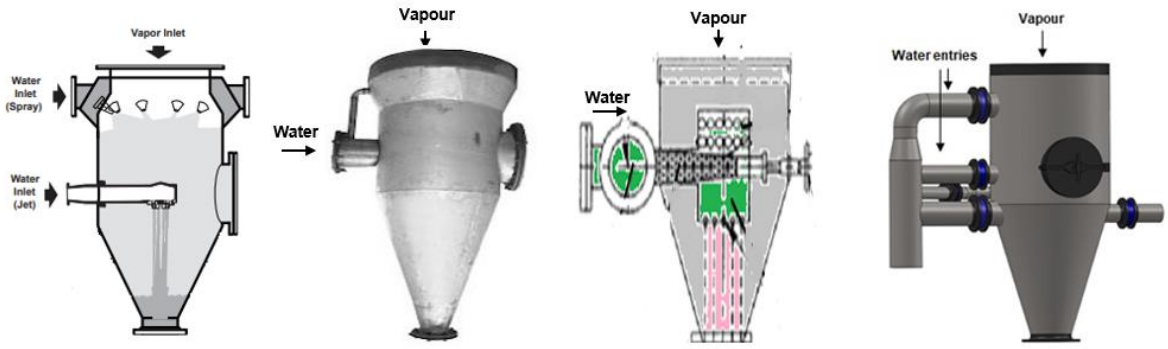

Figure 8. Jet condenser types (Schutte and Koerting, 2010; www.indiamart.com; www.sugarprocesstech.com).

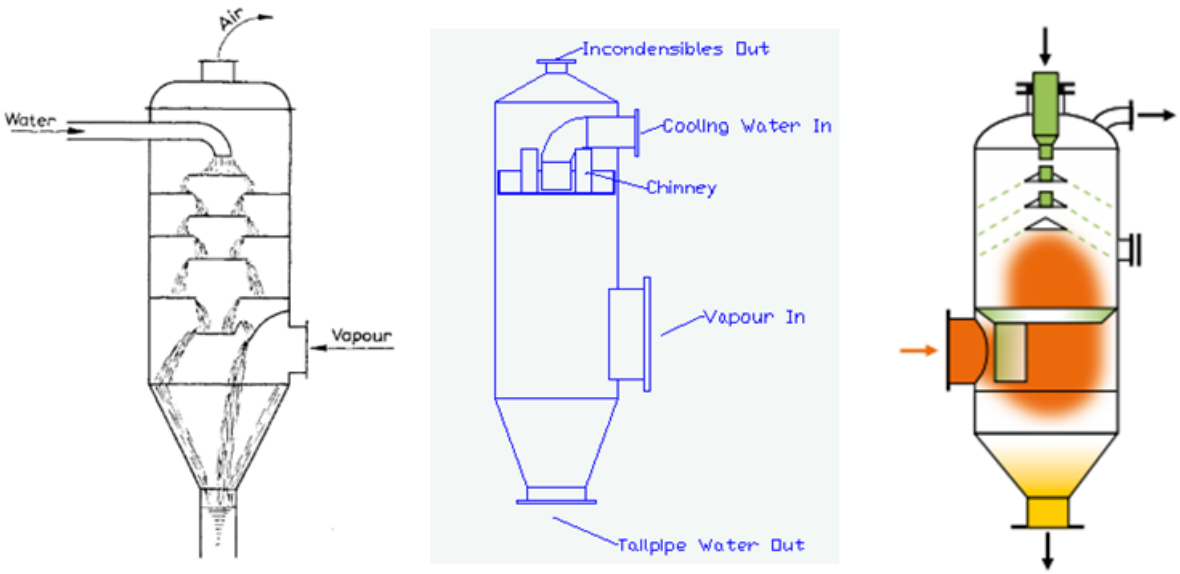

Figure 9. From left to right: Tray type, rain type and curtain nozzle condenser respectively (Hugot, 1986; www.sugartech.com).

The performance of direct contact condensers is determined by the approach temperature (vapour temperature – tail water pipe temperature). As the condenser performance improves, the approach temperature becomes smaller. Better performance requires less injection water. Thus, the power demand decreases significantly.

Conventional condensers work with an approach temperature in the range of 8-16 K and have a power requirement at the injection water system and cooling station in the range of 2.5-4 kWh/t cane. Modern open nozzle jet condensers or curtain nozzle condensers are able to work at an approach temperature of between 1.5-7 K. By reducing the approach temperature to an expected range of 3-7 K, the pumping power demand can be reduced by half because less water is pumped and therefore less power consumed. As such, there is a significant potential to save electrical power and earn additional revenue through exporting, and/or through bagasse savings.

The barometric curtain nozzle condensers are usually employed as central condensers. Figure 10 shows an installation of curtain condensers in a cane sugar factory in Brazil.

Figure 10. Curtain nozzle condensers at Barra Grande sugar factory, Brazil.

Case studies

Obviously not all available technologies can be applied easily to an existing factory. Investments need to be payback oriented. Usually payback periods of 2-3 years are acceptable. Another important aspect is to overcome traditional thinking which is one of the main hurdles for any improvement.

Some measures of how to reduce the energy demand of cane sugar factories are summarised in the subsequent paragraphs.

Mass and energy balances

Mass and energy balances can reveal the inefficiencies of plant operation and are the backbone of process optimisation and investment decisions. Often awareness of inefficiencies alone can help to reduce the steam demand by 1-3% on cane.

Mass and energy balances are also used to test various energy scenarios. This can lead to a stepwise reduction of factory energy consumption as projects with different payback periods are implemented in sequence.

A generic factory model has been worked out with the following characteristics summarised in Table 1.

Table 1. Basic data for the process calculations.

Cane crushing rate	t/day	8000	with backend refinery for the complete raw sugar production
Effective crop length	days	200	
Sugar content in cane	%	15,5	
Fibre content in cane	%	13,7	
Extraction		Diffuser	
Imbibition rate	% on fibre	286	
Boiler parameters	kPa/°C	3 200 kPa/400°C	
Live steam on cane	% on cane	75	
	t/h	250	
Exhaust steam	kPa	200	
	t/h	285,3	
Make up steam	t/h	168,9	
Coal requirement	t/season	32 083	
Coal cost	ZAR/year	36 895 129	
Specific power demand	kWh/t cane	20	
Power export	kWh/t cane	None	
Evaporators		Robert	4 effects

Because a lot of make-up steam is employed for the Base Case (Table 1), power saving is not required for the initial optimisation steps. As the bagasse amount is not sufficient, coal needs to be employed as a supplementary fuel.

A series of optimisation measures have been worked out reducing the steam demand step by step. The different measures and results are displayed in the following paragraphs.

Cold diffuser raw juice (Scenario 1)

Diffusers have the drawback that the temperature of raw juice is much higher compared to that out of milling tandems. Diffusers are required to be operated at higher temperature levels compared to mills, in order to keep microbiological sugar losses under control. This may seem beneficial at first view, but that is not the case since this hot raw juice presents a lost opportunity. Shifting the scalding juice to the second and third diffuser compartments allows the juice in the first stage to pass through the cold cane and to be cooled. Thus, the raw juice temperature can be reduced from 64 to 52°C. This scenario then offers the possibility to employ an additional juice heater operated with 3rd vapour, optimising the vapour bleeding arrangement at the evaporator train and therefore also offers a steam saving effect. This measure should have very minor impact on microbiological sugar losses as only the first compartments of the diffuser are affected. Also, starch removal should not be affected as the impact on the residence time of juice is small. The method to employ cold raw juice is standard in the beet sugar industry and a long proven energy saving measure. However, for cane diffusers practical experience still needs to be gained.

Switching scalding juice heating from 1st to 2nd vapour (Scenario 2)

Considering a slight increase in heating surface for the scalding and press water heaters, and switching from 1st to 2nd vapour will further improve the steam economy where possible.

Pan automation at R1 pans in the refinery (Scenario 3)

For raw and refinery pans often a lot of water is employed as pan movement water, reducing fine crystals formed spontaneously during crystallisation. With proper pan automation, the water addition can usually be at least reduced to 20% of the original water amount. This offers a lot of steam saving potential especially for the refinery section. For Scenario 3 pan automation has been considered for the R1 pans in the refinery. Subsequently also the pressure of exhaust steam needs to be increased by 30 kPa from 200 to 230 kPa which is usually feasible as long as the turbine drives and backpressure turbines have enough capacity. A drawback of steam saving measures is the requirement of additional evaporator heating surface. This effect can be countered by increasing the exhaust steam back-pressure moderately as this can limit the demand of additional heating surface. Sugar losses by inversion need to be considered as a slight potential drawback. Where falling film evaporators are employed in the first effects, the residence time drops drastically compared to Robert and also Kestner evaporators. Thus, sugar losses can be controlled by juice residence time reduction. However, the change of evaporator technology has not been considered for this scenario. Practical experience of the authors with many sugar factories optimised for high steam efficiency in Brazil, India and Pakistan have proven the feasibility to increase the exhaust steam pressure to a level of 2,3-2,5 bar without negative impact on sucrose inversion. The reason for this phenomenon is that the juice flow in the first two effects increases because of the lower water evaporation and therefore less residence time is calculated by juice holding volume divided by juice outlet flow volume. The capacity of the plant is not affected by these measures.

The results of the different optimisation scenarios are summarised in Table 2.

Table 2. Steam and coal saving results.

		Base scenario	Scenario 1: Cold diffuser juice	Scenario 2: Switch scalding juice from 1st to 2nd vapour	Scenario 3: Automation of R1 pans; exhaust pressure increase to 230 kPa
Steam on cane	% on cane	75	72,9	71,5	66,2
Exhaust steam consumption	t/h	250	243	238,42	220,7
Exhaust steam pressure	kPa	200	200	200	230
Make-up steam	t/h	168,9	161,8	157,29	136,8
Coal requirement	t/season	32 083	27 833	25 079	14 433
Coal cost	ZAR/year	36 895 129	32 007 579	28 841 386	16 598 315
Additional revenue	ZAR/year	-	4 887 550	3 166 193	12 243 071
Estimated payback			<one season	<one season	<one season

There are obviously many additional energy saving measures possible. The authors selected some measures which are not common in Southern Africa in order to highlight the potentials for plant efficiency improvements.

Conclusions

Energy saving can be a lucrative investment with special regard to avoiding fossil fuels like coal in order to reduce operation cost. In order to determine the steam/coal saving potential and in order to predict the impact of optimisation measures, a mass and energy balance of the factory is essential. Once the present operation of a factory is well known, optimisation measures can be worked out. Based on a generic factory model with a backend refinery, a series of steam saving measures allow the reduction of coal consumption from 32 083 t/year to 14 433 t/year resulting in an overall saving potential of 20 296 814 ZAR/year.

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