

The inversion of sucrose is undesirable in a sugar factory as the primary objective is to maximise the recovery of sucrose from the sugarcane syrup/molasses in its crystalline form; hence, inversion represents a direct loss of sucrose. The loss due to sucrose inversion contributes to the weekly Undetermined Loss (UDL) figure reported by sugar factories. An UDL above 1.8% is generally regarded as high for raw sugar factories (Rahiman *et al.*, 2019). However, it may be preferable for individual raw sugar factories to consider their historical best UDL given their current factory configurations. Chemical inversion of sucrose in raw sugar factories is responsible for approximately 67% of the UDL under acceptable levels of sucrose loss (Anon, 2012a). Therefore, it is important for sugar factories to utilise reliable methods for estimating the loss due to sucrose inversion.

Amongst the available methods of estimating Sucrose Inversion Loss (SIL), the Schöffler method (Schöffler *et al.*, 1985) and the Vukov (1965) acid hydrolysis model remain the preferred options for raw sugarcane factories (Rein, 2007). The Schöffler method is an analytical method for estimating SIL that utilises the changes in the measured G/Brix (or G/B) ratios between the inlet and outlet of a vessel or process, whereas the Vukov model can be regarded as a theoretical method of predicting the amount of inversion from four factors, viz. brix, pH, temperature and retention time. Given the conditions (brix, pH, temperature and residence time) in a raw sugar factory, the Vukov (1965) model predicts that most sucrose inversion can be expected across the evaporator station, particularly in the first and second effects where the sugarcane juice/syrup generally has a lower brix (10-30°Bx) and is exposed to higher temperature conditions (90-120°C). Sucrose inversion loss surveys across raw sugar evaporator stations, that utilised the above-mentioned estimation methods, have shown that the Vukov model underestimates the amount of sucrose inversion when compared to the Schöffler equation (Dairam *et al.*, 2016; Rahiman and Balkissoon, 2017).

In recent times there have been concerns among sugar technologists that if glucose is destroyed during evaporation, this would affect the reliability of the SIL that is calculated using the Schöffler equation. However, Schöffler *et al.* (1985) did show that if glucose destruction was compensated for in the first evaporator effect, even under extreme temperature conditions (135°C instead of the usual 120°C), there would be a minimal increase in the calculated SIL.

Given this background, the objective of this paper is to present a literature review on (1) factors affecting the rate of sucrose inversion, (2) available numerical models used to predict SIL and their applicability to a raw sugar evaporator station, (3) available analytical methods of estimating SIL and their reliability in a raw sugar factory evaporator station and (4) comparisons between the model and analytically measured SILs.

Factors affecting the rate of sucrose inversion

The hydrolysis of sucrose in an aqueous solution is regarded as a pseudo-first-order reaction (Honig, 1953; Vukov, 1965; Mauch, 1971; Schöffler, 1984) concerning sucrose, particularly when water is in great excess. The integrated form of the rate equation (Anon, 2019a) for the first order reaction is defined by Equation 2.

$$S_t = S_0 e^{-kt} \dots \text{Equation 2}$$

where S_t represents the sucrose concentration after time t (min), S_0 is the initial sucrose concentration and k is the reaction rate constant (min^{-1}). Besides the concentration of sucrose, the reaction rate constant, k , depends on the following:

1. pH
2. Temperature

3. Salt concentration

The effect of the above-mentioned factors on the rate of SIL is detailed in the sections that follow.

Dependence on pH

During inversion, the key step is the cleavage of the oxygen-carbon bond that binds the monosaccharides in the sucrose molecule which, in turn, allows for the release of the D-glucose and D-fructose molecules. The cleavage of the oxygen-carbon bond is catalysed by the presence of hydrogen ions and is therefore dependent on the concentration of these ions. The concentration of hydrogen ions can be inferred from pH as pH is a logarithmic measure of the hydrogen ion concentration at a particular temperature. The pH of a solution indicates the level of alkalinity and acidity and the pH scale typically ranges from 0 (highly acidic) to 14 (highly alkaline). The pH of pure water decreases as the temperature of water increases because the temperature increases the rate at which water molecules ionise into hydrogen ions (i.e. hydrogen ions bonded to water molecules) and hydroxide ions. For example, the pH of pure water is 7.00 at 25°C and 6.63 at 50°C (Anon, 2019b). However, for pure water, this does not imply that the water has become more acidic; it simply means that the neutral point has shifted.

Similarly, Schäffler (1987a) showed that the pH of sugarcane juices decreases with increasing temperature and a correlation for sugarcane juices was therefore developed to estimate the change in pH with temperature (correlation coefficient = 0.91). Catch samples that included mixed juice (MJ), clear juice (CJ) and syrups (SP) from five different South African factories (about 80 samples) were used to develop the correlation (Equation 3).

$$\frac{dpH}{dT} = -0.0339 + 0.015pH_{25} - 0.0017pH_{25}^2 \dots \text{Equation 3}$$

where T in is the sample temperature (°C) and pH₂₅ is the pH measured at 25°C. Equation 3 can be used for samples that have temperatures ranging from 25 to 85°C. However, Schäffler (1987a) reported that Equation 3 may be extended to 125°C, however, it should be noted that the extension was based on the pH measurements of only two CJ samples.

Sucrose degrades readily under acidic conditions and Schäffler (1984) reported a ten-fold increase in the SIL reaction rate for a unit drop in pH. Conversely, the hydrolysis of sucrose under alkaline conditions is very slow, as the linkage between the glycosidic groups is quite stable when compared to acidic conditions. Mauch (1971) reported that the minimum reaction rate for the hydrolysis of sucrose is between a pH range of 7.5 and 8.5 for the temperature range of 60 to 140°C, based on the work of Saprano and Kharin (1969¹), which is in agreement with the findings of Schäffler (1984). The pH (measured at room temperature) of CJ supplied to a raw sugar factory evaporator station [(also referred to as Evaporator Supply Juice (ESJ))] typically ranges from 7.0 to 7.4 (Anon., 2012b), and the equivalent pH at operating temperature is expected to be <7, hence there is no need to explore the hydrolysis of sucrose under alkaline conditions any further.

Dependence on temperature

The Arrhenius equation (Anon, 2019c) may be used to describe the dependence of the reaction rate constant on temperature (see Equation 4).

¹ The paper by Saprano and Kharin (1969) was not available in the SMRI database, nor in the public domain; however, the key findings are reported by Mauch (1971).

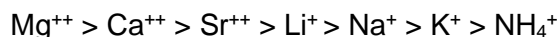
$$k = Ae^{\frac{-E}{RT_{abs}}} \dots \text{Equation 4}$$

where A is the frequency factor (determined empirically), E is the activation energy (kJ/mol), R is the gas constant (kJ/mol/K) and T_{abs} is the absolute temperature (K). According to Equation 4, the reaction rate constant increases exponentially with temperature assuming that the activation energy remains constant. If the activation energy is assumed to be constant, then the decadic exponent (E/R) as referred to by Vukov (1965), in Equation 4, may be determined by finding the gradient of the plot $\ln(k)$ versus $(1/T_{abs})$ [Anon, 2019c]. Vukov (1965) and Parker (1967) reported decadic exponents of 5670 K and 5810 K, respectively.

Vukov (1965) reported an average activation energy for sucrose inversion of 108.42 kJ/mol, from the work of ten authors, which was calculated for a temperature range of 20 to 130°C. The activation energy is theoretically independent of temperature as it is the minimum amount of energy required for a reaction to take place. However, the minimum amount of energy required will be reduced by the presence of a catalyst. According to Mauch (1971), many authors have reported that the energy of activation for sucrose hydrolysis reduces with temperature, and this may be due to the inconsistency of the hydrogen ion concentration (the hydrogen ion catalyses sucrose hydrolysis and its concentration in water depends on temperature).

Dependence on salts

Both Vukov (1965) and Mauch (1971) reported that the hydrolysis of sucrose depends on the presence of neutral salts, or anions and cations. The effect of salts was realised when different acids and bases were used to buffer sucrose solutions in hydrolysis experiments. For alkaline buffers (Mauch, 1971), the hydrolysis of sucrose was accelerated by the following cations, in decreasing order:



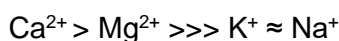
And for acidic buffers, the hydrolysis of sucrose was accelerated by the following anions, in decreasing order:



Vukov (1965) described the catalytic effect of salts, in decreasing order, as follows:

Disodium phosphate > Calcium lactate > Potassium chloride > Sodium glutamate

Rackemann and Marasinghege (2023) provided detailed findings on the impact on sucrose inversion of non-sucrose such as salts, invert sugars, amino acids, flavonoids, polysaccharides and bagacillo present in Australian sugarcane juices. The experiments involved spiking clarified juice with non-sucrose such that the final concentration was approximately five-fold greater, and thereafter exposing the juice (11°Bx) to conditions experienced in the first effect evaporator station of a raw sugar factory (temperature of 120°C and pH of 6.6 and 7.6), i.e. the area in the evaporator station where the highest amount of sucrose hydrolysis is expected. The results suggest that salts (e.g. KCl, MgCl₂, CaCl₂ and NaCl) and amino acids present in the juice have the highest catalytic effect on sucrose degradation, whereas organic acids reduce the rate of sucrose hydrolysis due to their pH-buffering effects. Furthermore, it was shown that the catalytic effect of the cations present in salts are in decreasing order, as follows:



This is similar to what was reported by Mauch (1971).

The inorganic constituents of MJ include potassium, sodium, calcium, chloride, sulphates, iron, magnesium, silica and phosphates (Anon, 2012c). The monovalent ions are largely unchanged during clarification; however, magnesium, silicates, sulphates and phosphates are partially removed (Rein, 2007). Calcium ions in the limed juice react with the inorganic phosphates to produce the precipitate and the final calcium ion concentration is typically slightly higher than the initial concentration in MJ. In a raw sugar factory, the soluble inorganic constituents contribute to the conductivity ash measurement; therefore, the effect of ash on the hydrolysis of sugarcane solutions should not be ignored. Unfortunately, the numerical model for determining the effect of salts on the reaction rate constant by Vukov (1965) was determined on 1st and 2nd carbonated beet juices for limited temperature and brix ranges of 80 to 120°C and 10 to 20°Bx, respectively. Rackemann and Marasinghege (2023) reported work on the effect of salt on Australian sugarcane juice, but only at a specific temperature and brix, and a limited pH range. Therefore, there is further scope for understanding the catalytic effect of salts or conductivity ash on the hydrolysis of sugarcane juices.

Numerical models used to estimate the rate of sucrose hydrolysis

Among the models utilised to estimate sucrose inversion loss for wide limits of pH, temperature and brix conditions, the Vukov (1965) and Parker (1967; 1970) numerical models are available options. A detailed account of each model follows:

The Vukov (1965) model

Vukov (1965) derived three numerical models for determining the rate of sucrose hydrolysis. Each model considers the influence of the sucrose/water concentration and temperature; however, they differ in that each model contains factors to account for either the hydrogen ion concentration (pH), the hydroxide ion concentration (pOH) or the salt concentration. It is the sum of the reaction rate constants from each model that determines the net reaction rate as per Equation 2. However, in sugarcane processing, the effects of alkalinity and salt concentration are often ignored. Ignoring alkalinity is reasonable, since the pH conditions in raw cane sugar factories seldom exceed a pH₂₅ of 8; however, the effect of salts should not be ignored.

The frequently-used model, referred to as the Vukov model in the 'Introduction' section of this paper, is shown in Equation 5, and focuses on the hydrolysis of sucrose catalysed by hydrogen ions. Vukov (1965) derived this formula from the experimental results of 12 authors, who used mostly pure technical solutions. Of these 12 authors, Honig (1959) reported sucrose inversion rates using sugarcane-derived refinery liquor and technical sugarcane solutions with a purity range of 94.5% to 100%. There is thus scope for deriving reaction rate data using sugarcane juice from a raw cane sugar factory.

$$\log k = 16.91 + \log(\rho - S) - \frac{5670}{T} - pH \dots \text{Equation 5}$$

where $(\rho - S)$ represents the water concentration (g/mL), ρ stands for the density of the solution (g/mL) and S is the sucrose concentration (g/mL). The water concentration term $(\rho - S)$ in Equation 6 may be replaced with the term $[\rho(100-B)/100]$, as follows:

$$\log k = 16.91 + \log\left[\rho\left(\frac{100-B}{100}\right)\right] - \frac{5670}{T} - pH \dots \text{Equation 6}$$

where B is the brix of the solution (i.e. the dissolved solid content of the solution determined by refractometry). Caution should be exercised when using Equation 6 for molasses, particularly final molasses, as brix is not regarded as a true measure of dissolved solids (Rein, 2007). Equation 6 is ideally valid for pure sucrose solutions, for a brix range of 0 to

72.5°Bx (equivalent to the sucrose concentration of 0 to 9 g/mL), a pH range of 1 to 6.5 and a temperature range of 20 to 130°C. Vukov (1965) concluded his work by stating that the model (Equation 5) is applicable to concentrations not exceeding 55°Bx; however, this is not in agreement with the equivalent brix for the sucrose concentration (0 to 9 g/mL) given by Vukov (1965). In contrast, Rein (2007) stated that the brix range for Equation 6 is 7 to 70°Bx which is close to the equivalent brix range mentioned earlier on. According to Vukov (1965), Equation 7 is also valid up to a pH of 7.4. It is unclear whether the pH mentioned by Vukov (1965) refers to the pH measured at 25°C (pH₂₅) or the pH measured at the operating temperature (pH_T). According to Schäffler (1987a), Vukov's personal communication was that the pH must be measured at the operating temperature (pH_T). Rein (2007) agreed with Schäffler (1987a) regarding pH being measured at the operating temperature, but also added that pH must be corrected for dilution, as dilution of a sample with water increases the pH. As a result, through personal communication with Schäffler, Rein (2007) proposed Equation 7 to correct for sample dilution. For example, using Equation 7, if a sugar solution is diluted from 80 to 40°Bx, then the pH of the dilute solution would be 0.56 (i.e. 40 x 0.014) units higher than the pH of the solution at operating brix. Rein (2007) implied that the pH used in Equation 6 should be measured at the operating temperature and the operating brix.

$$\frac{dpH}{dB} = -0.014 \dots \text{Equation 7}$$

It is unknown whether Equation 7 applies to all raw sugar factory juices, syrups, molasses and massecuites. According to Vukov (1965), the calculated inversion data from his models were in good agreement with factory measurements as the majority of the predicted inversion loss results showed a deviation of <25% from the actual measurements, which Vukov regarded as acceptable. Rein (2007) regarded the Vukov model as the best predictor of inversion loss provided that temperature and dilution corrections were applied to pH.

The Parker (1967) model

The first mention of Parker's sucrose hydrolysis model was in 1967; however, a detailed account of his work was given only in 1970. Parker (1970) mentioned that most previous literature on sucrose hydrolysis was based on dilute sucrose solutions and that polarimetry was utilised to estimate the amount of inversion. Hence, there was limited reliable sucrose hydrolysis data for the determination of inversion under refinery conditions. Therefore, Parker conducted experiments to assist with reliably determining the rate of sucrose hydrolysis under sugar refinery process conditions.

Parker (1970) used pure sucrose solutions that were held at various temperatures and pH conditions such that an inversion of 10% was not exceeded over the 1.5 hour run period. Some of the solutions contained chlorides of Na, K, Ca and Mg. The reducing sugar concentration was deemed to be an accurate measure of inversion as it was stated that both glucose and fructose are sufficiently stable between pH values of 2 to 6. The reducing sugar concentration was measured using a special cuprimetric method² that had an accuracy of ±0.05%. The pH of the sucrose solutions was measured at operating temperature and kept constant to within ±0.001 units over the run period by addition of appropriate buffers.

The 11 tests containing chloride salts suggested that salts had a marginal effect on sucrose hydrolysis, and the first order rate constant could be determined by using Equation 8:

$$\log k = 15.30 - \frac{5810}{T_{abs}} - pH_T + \log (C_W - C_S) \dots \text{Equation 8}$$

² The cuprimetric method is a colorimetric procedure that makes use of a copper reagent for determining reducing substances, including reducing sugars.

where C_W and C_S are the molar concentrations (mol/L) of water and sucrose, respectively, at the operating temperature. Parker's model is valid for a brix range of 6 to 70°Bx, a temperature range of 25 to 85°C and a pH range of 1 to 6. According to the author, the C_W and C_S terms are calculated by using Equations 9 and 10, respectively:

$$C_W = \frac{100-B}{1.8} \times \rho_{\text{solution at } T} \dots \text{Equation 9}$$

$$C_S = \frac{B}{34.2} \times \rho_{\text{solution at } T} \dots \text{Equation 10}$$

In Equations 9 and 10, $\rho_{\text{solution at } T}$ refers to the density (g/mL) at the operating temperature. Rein (2007) reported that the inversion rates from the Parker model were lower compared to the Vukov model.

Applicability of the numerical models of estimating the SIL across an evaporator station

This section considers the typical operating conditions across evaporator stations to assess the applicability of the Vukov and Parker models in predicting SIL.

Typical evaporator operating conditions

Table 1 is a summary of the brix, pH and temperature operating ranges measured across South African evaporator stations (Schäffler, 1987b; Schäffler, 1988; Davis, 1995; Barker and Madho, 2008; Madho, 2011; Barker, 2012; Dairam *et al.*, 2016) as well as the ranges of application for both the Vukov (1965) and Parker (1967) acid hydrolysis models. It was assumed that the temperature of the juice in the 1st effect evaporator would not exceed 120°C and the temperature of the syrup would not fall below 59°C, hence the pH reported in Table 1 is at the operating brix and the assumed temperatures (using Equations 3 and 7). It is clear from Table 1 that the Vukov model is more applicable than the Parker model to the conditions prevalent across South African evaporator stations.

Table 1. Typical operating conditions across South African evaporator stations and the ranges of applicability for the Vukov and Parker models

Parameter	Factory ranges from literature	Vukov model applicability range	Parker model applicability range
Brix (°Bx)	9.5 (ESJ) to 72.3 (syrup)	0 to 72.5	6.0 to 70.0
pH at operating temperature	5.7 (syrup at 59°C) to 5.9 (ESJ at 120°C)	1.0 to 6.5	1.0 to 6.0
[pH at 25°C]	[5.8 (syrup) to 7.4(ESJ)]		
Temperature (°C)	60 (syrup) to 113 (ESJ)	20 to 130	25 to 85

Comparison between the Vukov (1965) and the Parker (1967) models

Figures 1a and 1b compare the Vukov and Parker models for the SIL predictions at 25°Bx and 70°Bx, respectively. The conditions were chosen so that the predictive power of the models could be tested at low and high brix scenarios. The pH and temperature ranges were chosen around the average conditions experienced in the first and last effects of the evaporator station for the 25°Bx and 70°Bx scenarios, respectively, whilst taking into consideration the operating ranges for both the Vukov and Parker models (an exception was made for the Parker model regarding its temperature limit). A juice/syrup retention time of one hour was used in the

calculations. It is observed that the levels of SIL are higher in the low brix scenario and this is in agreement with Dairam *et al.* (2016) and Rein (2007). The Parker model pH 5 and Vukov model pH 6 trends are not clearly visible in Figure 1b as they are overlaid by other trends that are close to the x-axis. Overall, it is evident from Figures 1a and 1b that the loss predicted by the Parker model is substantially lower than that predicted by the Vukov model, which is in agreement with Rein (2007).

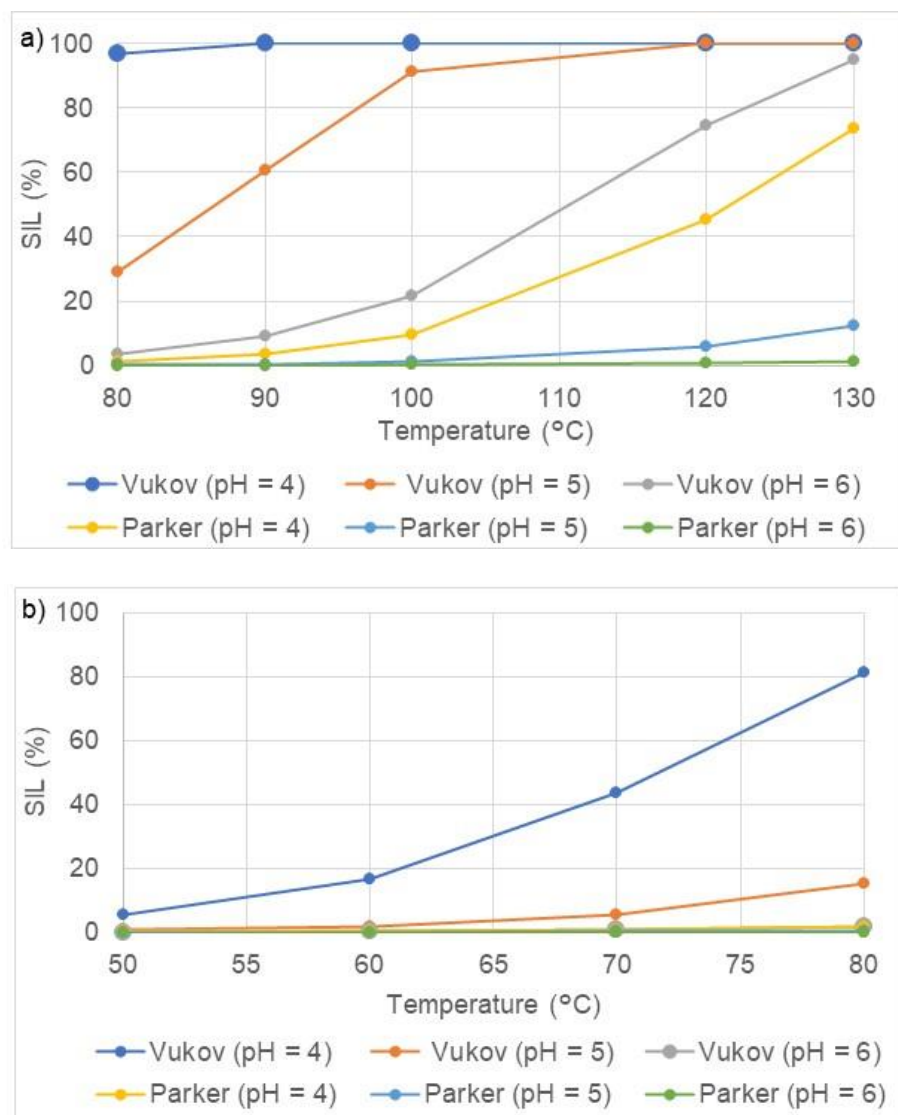


Figure 1. Comparison between the SIL estimated by the Vukov and Parker models at a) 25°Bx and b) 70°Bx

Dairam *et al.* (2016) conducted several evaporator inversion loss tests at the Gledhow sugar factory and concluded that the Vukov model underestimated the SIL across the raw sugar factory evaporator station when compared to the measured SIL, using the Schäffler method. Therefore, it is expected that the SIL estimated using the Parker model would be even lower compared to the measured SIL; hence it may not be advisable to use the Parker model for raw sugar factory process streams.

Analytical methods for measuring SIL

The analytical methods for measuring SIL typically include the measurement of analytes such as sucrose, glucose, fructose, brix, chloride and pH. The measurement of the pH of a solution

is complicated as the value depends on whether the sample pH was measured at operating temperature or room temperature and/or whether the sample was measured at operating brix or after dilution (see the 'Factors affecting the rate of sucrose inversion' for more details). Some authors did not give details about the conditions under which pH was measured, which will, in turn, affect the interpretation of results; therefore, the interpretation of results using pH should be exercised with caution.

SIL measurements are typically performed across unit operations that have single input and output streams. Analytical methods of measuring sucrose inversion loss may be regarded as indirect and direct. Indirect measurement of SIL involves assessing the changes in chemical markers to gauge the extent of the inversion loss, whereas the direct measurement of SIL calculates the differences in the sucrose content. Both are typically expressed as a percentage of the sucrose in the incoming material. Both indirect and direct measures of sucrose inversion will be explained in the following sections:

Indirect measures of SIL

Several evaporator inversion studies have been conducted in the past; for example, Schäffler *et al.* (1985), Purchase *et al.* (1987), Davis (1995), Wong Sak Hoi and Tse Chi Shum (1996), Barker and Madho (2008), Madho (2011), Barker (2012), Dairam *et al.* (2016) and Rackemann and Broadfoot (2016). Table 2 is a summary of the most extensive evaporation inversion loss surveys reported in literature (i.e. surveys that were conducted for lengthy periods of time and/or across many raw sugar factories). Based on this work, potential chemical markers that may be used to gauge the extent of the sucrose inversion loss include changes in the sucrose/brix (S/B), sucrose/chloride (S/Cl), glucose/brix (G/B), glucose/chloride (G/Cl), glucose/sucrose (G/S), fructose/brix (F/B), fructose/chloride (F/Cl), fructose/sucrose (F/S) and reducing sugar/sucrose (F+G/S) ratios. These chemical markers are typically expressed as a percentage change in the ratio. Nowadays, the composition (brix, pol, sucrose, glucose, fructose, ash and colour) of raw sugar factory process streams can be rapidly determined using the SMRI Near Infrared Spectroscopy (SMRI-NIRS) technology. The SMRI-NIRS technology is a cost-effective alternative to the conventional gas chromatography method of analysing for F, G and S.

Table 2. Summary of extensive evaporation surveys reported in literature

Reference	Name of sugar factory	Streams sampled	Sampling*
Schäffler <i>et al.</i> (1985)	<ul style="list-style-type: none"> Darnall 	ESJ, ESJ after juice heaters and syrup from effects 1, 3 and 4.	A fixed sampling interval of 15 min across 4-6 h over four consecutive days.
Purchase <i>et al.</i> (1987)	<ul style="list-style-type: none"> Felixton Malelane Mount Edgecombe Noodsberg Pongola 	CJ, syrup after the second effect and syrup from the last effect. Vapour 1, 2 and 3 condensates.	Samples were taken every shift for one week for every month of the 1986-87 season.
Wong Sak Hoi and Tse Chi Shum (1996)	<ul style="list-style-type: none"> Britannia Deep River Beau Champ (DRBC) Medine Mon Désert Alma (MDA) 	ESJ, and syrup exiting each evaporator vessel were sampled.	<p>Samples were taken every 10 min, with a 5 min time lag between vessels. One hour duration sampling was performed for each stream.</p> <p>At Union St Aubin, there were three trials conducted</p>

	<ul style="list-style-type: none"> • Société de Sucrière de Rivière du Rempart (SSRR) • St Félix • Union St Aubin 		in 1994 and in the same year, the number of trials conducted at the other factories was not stated.
--	--	--	---

*Preservation with mercuric chloride solution and/or freezing was employed by Schäffler et al. (1985) to prevent sample deterioration. Wong Sak Hoi and Tse Chi Shum (1996) utilised mercuric iodide solution and deep freezing, as well as formaldehyde and deep freezing for the preservation of samples. Sample preservation was not reported by Purchase et al. (1987) but it may be assumed that at least rapid freezing of the samples was employed.

Schäffler et al. (1985) reported that the mean brix/chloride (B/Cl) ratio (normalised on clear juice and expressed as a percentage) was on average 100% \pm 0.4 units across the evaporator effects sampled, indicating that brix was not preferentially destroyed when compared to chloride; hence, brix or chloride may be used as a reference marker. Wong Sak Hoi and Tse Chi Shum (1996) concurred with this finding. Although chloride may be used as a reference marker, brix is typically preferred as this analyte can be measured more easily and more cost-effectively at a factory than can the chloride ion.

Ideally, the chemical marker used to assess sucrose inversion loss should have the following three properties:

- It can detect sufficiently low levels of sucrose loss
- It is stable under typical evaporator conditions (pH, temperature and residence time), particularly the products of sucrose inversion
- It does not partake in any other reaction except the inversion reaction.

According to Honig (1963), sucrose inversion loss across evaporator stations should not exceed 0.2% of the sucrose in the ESJ. Rackemann and Broadfoot (2016) reported that a 1% sucrose loss across the evaporator station represents a substantial loss of sugar. The reduction in sugar produced is a result of (a) the direct loss of sucrose due to inversion and (b) the increased loss of sucrose to final molasses due to the reduction of the purity of syrup going to the pan floor.

To select the most sensitive chemical marker of sucrose loss, an attempt was made to quantify the change in chemical marker (for example, $\Delta S/B$, $\Delta G/B$, etc.) associated with various levels of sucrose loss across the evaporator station (see Table 3). The following assumptions were made in the calculations:

- ESJ is supplied at 13°Bx having a gravity purity of 85% and syrup exits at 65°Bx.
- The average ESJ glucose and fructose concentrations are 0.37% and 0.41%, respectively.
- There are no physical losses³ across evaporation, i.e. the mass of brix that enters in ESJ exits in the syrup.
- Glucose and fructose are not destroyed during evaporation.
- Sucrose losses are only due to the hydrolysis of sucrose.

In addition, the analytical precision associated with each chemical marker was determined using the analytical precision of the individual analytes (Pillay, 2018; Walford, 2020⁴) and the

³ Physical loss of sucrose may at times represent a significant source of sucrose loss in the evaporator station.

⁴ Personal communication with S Walford, 2020.

Monte Carlo simulation technique (Walford, 2020⁵). The results in Table 3 suggest that the most sensitive indicators of sucrose loss are as follows, in descending order:

$$\Delta(F+G/S) > \Delta(F/B) \approx \Delta(F/S) > \Delta(G/S) \approx \Delta(G/B) > \Delta(S/B)$$

In addition, the results in Table 3 also confirm the reasoning of previous literature (Schäffler *et al.*, 1985; Purchase *et al.*, 1987) that gravity purity difference is not a sensitive indicator of sucrose loss as losses of <3.4% (determined by calculation) across the evaporator station yield $\Delta(S/B)$ values that are smaller than the analytical precision.

Table 3. Summary of the sensitivity of chemical markers used for monitoring inversion

Sucrose Loss (%)	%Change in chemical markers (Syrup-ESJ) equivalent to the evaporator station sucrose loss					
	$\Delta(S/B)$	$\Delta(F+G/S)$	$\Delta(G/B)$	$\Delta(F/B)$	$\Delta(G/S)$	$\Delta(F/S)$
0.2	-0.17	0.21	0.09	0.09	0.11	0.11
0.5	-0.42	0.53	0.22	0.22	0.26	0.26
1.0	-0.85	1.06	0.45	0.45	0.53	0.53
1.5	-1.28	1.60	0.67	0.67	0.80	0.80
2.0	-1.70	2.15	0.89	0.89	1.07	1.07
Analytical precision (\pmunits)	± 2.85	± 1.04	± 0.62	± 0.56	± 0.73	± 0.69

Before selecting an appropriate chemical marker(s) from the above table, it is important to understand the stability of the reducing sugars under the evaporator operating conditions (i.e. pH and temperature). It is also important to explore the possibility of the hydrolysis of polysaccharides being a potential source of reducing sugars (almost exclusively glucose) as this may falsely inflate the SIL determined using reducing sugar ratios.

Stability of glucose and fructose across a raw sugar factory evaporator station

In the event of over-liming of MJ during clarification, the ESJ may potentially be alkaline. The decomposition of glucose and fructose occurs more rapidly under alkaline conditions than under acidic conditions. The decomposition products of the invert sugars depend on the prevailing temperature and pH conditions at the time of reaction (Mauch, 1971); however, the products include dark-coloured substances, melassigenic substances and/or organic acids such as lactic acid (Mauch, 1971; Schäffler, 1984). Typically, though, the pH of ESJ measured at room temperature ranges from 7.0 to 7.4 (see Table 1) and is therefore only slightly alkaline at best; hence, the rapid destruction of inverts across an evaporator station is not typical.

As stated in Table 1, the pH at room temperature across the evaporator station typically decreases from ESJ (pH 7.4) to syrup (pH 5.8) suggesting that the syrup gradually becomes acidic along the station. Invert sugars are reasonably stable under acidic conditions (with a pH range of 2-6) as reported by Parker (1970). Reviews conducted by Schäffler (1984) and Mauch (1971) revealed that under acidic conditions, especially when the pH < 4.3 and the temperature >120°C, the resulting invert sugars (particularly fructose) degrade to form hydroxymethylfurfural as reaction time increases, which may later degrade in a second reaction to form levulinic and formic acids. Fortunately, the pH in an evaporator station typically does not fall below 4.3 nor does the juice temperature in the first effect exceed 120°C. Wong Sak Hoi and Tse Chi Shum (1996) stated that the work of Mega and van Etten (1988) suggested that D-glucose and a fructose carboxonium ion are formed during acid-catalysed sucrose hydrolysis, depending on the availability of water. The fructose carboxonium ion reacts with water to form D-fructose (this is to be expected in the 1st and 2nd evaporator effects

⁵ Personal communication with S Walford, 2020.

as water is abundant) or it may react with sucrose to form kestoses (latter evaporator effects). Thus, fructose seems to be more unstable than glucose during evaporation.

Schäffler *et al.* (1985) found that fructose was more labile than glucose across the evaporator station and they demonstrated this by plotting the F/G profile across the evaporator station. The destruction of fructose ranged from 3.6 to 5.4% from ESJ to syrup. Although fructose is more labile than glucose across a raw sugar factory evaporator station, it does not mean that glucose is not destroyed during evaporation. In Schäffler's (1984) review of the kinetic work on estimating sucrose and invert losses, it was shown that the destruction of glucose could be estimated using the Sapránov rate equation (Sapránov and Kolschewa, 1975), which is as follows:

$$\log_{10}k_G = 25.0 - \frac{10260}{T} - 0.017T + 0.77pH_T \dots \text{Equation 11}$$

where k_G is the first order degradation constant of glucose (min^{-1}), T is the temperature (K) and pH_T is the acidity at the operating temperature. The above equation is valid for a $pH \geq 4.5$ and temperature range of 60 to 140°C. Schäffler *et al.* (1985) incorporated Equation 11 in Equation 12 to determine the overall $\Delta(G/B)$ by compensating for glucose destruction:

$$\left(\frac{G}{B}\right)_{made} = \frac{\left(\frac{G}{B}\right)_{out}}{(e^{-k_G t})} - \left(\frac{G}{B}\right)_{in} \dots \text{Equation 12}$$

where t is the juice/syrup residence time in the evaporator. Since the pH across the evaporator is expected to decrease from ESJ to syrup, it follows that the 1st effect evaporators experience the highest pH levels. Schäffler *et al.* (1985) used extreme temperature conditions (135°C) across the 1st effect Kestner and estimated that the compensation for glucose destruction would only increase the sucrose loss across the evaporator vessel by 0.03 percentage units; hence, the impact of glucose destruction on SIL across the evaporator station may be regarded as minimal. Therefore, it seems that $\Delta(G/S)$ and $\Delta(G/B)$ are more reliable chemical markers than $\Delta(F+G/S)$, $\Delta(F/B)$ and $\Delta(F/S)$.

Hydrolysis of polysaccharides across a raw sugar factory evaporator station

A possible oversight in the evaporator inversion work referenced in Table 2 is that none of the authors considered the hydrolysis of polysaccharides as a source of glucose. The total soluble polysaccharides present in sugarcane process streams are referred to as gums (i.e. the total polysaccharides precipitated by acidified alcohol). Gums comprise of a variety of different polysaccharides; however, emphasis is usually given to starch and dextran as the former is readily transferred to the raw sugar crystal and adversely affects refining, whilst the latter adversely affects the raw sugar crystallisation process and quality (Rein, 2007). Both starch and dextran are made up of multiple glucose molecules; the former polysaccharide occurs naturally in the sugarcane plant whilst the latter is a product of microbial degradation of sucrose, which is enhanced in situations where sugarcane deterioration is poorly controlled.

According to Rein (2007), the insoluble starch granules entering with the sugarcane are gelatinised when heated in the sugarcane juice and later solubilised during further mixed juice heating and liming. Acid and enzymatic hydrolysis of starch are the two primary methods of breaking down starch. The acid hydrolysis of starch is typically performed under low pH conditions (pH range from 1 to 2) and temperatures ranging from 150 to 250°C, whereas enzymatic hydrolysis is usually carried out at low temperatures ($\leq 100^\circ\text{C}$) and pH levels close to neutral (Kolusheva and Marinova, 2007). It was mentioned earlier that the pH of ESJ measured at room temperature is typically neutral to slightly alkaline, and it is expected that the juice temperature in the first evaporator effect will not exceed 120°C; therefore, the acid hydrolysis of starch is expected to be minimal. Even if the starch is treated with alpha-amylase

enzymes during evaporation, the hydrolysis products are expected to be a mixture of polysaccharides and oligosaccharides, which are known as maltodextrins (Bednarska, 2015; Nel, 2021⁶).

Dextran is typically produced by *Leuconostoc mesenteroides* and other bacteria. Like starch, dextran is typically broken down by enzymatic or acid hydrolysis; however, the former is seldom applied in sugarcane processing as it is expensive and specific to the structure of the dextran present. Acid hydrolysis is typically carried out at a pH of around 1 (Hamdy *et al.*, 1956) and is accelerated at high temperatures. In addition, the optimal pH for storing dextran in solution is 6.5, preferably at room temperature. At a neutral pH and a temperature of 100°C, the rate of dextran hydrolysis is very slow compared to a pH of 1 (Anon, 2021). Thus, it is expected that the degradation of dextran in clear juice would be minimal and it is more likely that the dextran would break down to shorter-chained polysaccharides as opposed to breaking down to glucose. Therefore, it is unlikely that starch and dextran would be potential sources of glucose across the evaporator station, hence reinforcing the earlier suggestion that glucose-based chemical markers should be used for SIL measurements. It is unknown whether the other gums present in sugarcane juice or syrup may be potential sources of reducing sugars across the evaporator station, and they could therefore be considered in future work, although it is unlikely considering their similarity to starch and dextran.

Direct measures of SIL

The most frequently used equation to directly assess SIL is the Schöffler equation (Schöffler *et al.*, 1985) as shown in Equation 13:

$$SIL = \frac{\left(\frac{G}{B}\right)_{out} - \left(\frac{G}{B}\right)_{in}}{\left(\frac{S}{B}\right)_{in}} \times \frac{MM_S}{MM_G} \times 100 \dots \text{Equation 13}$$

where SIL is the sucrose inversion loss expressed as a percentage of the sucrose entering the unit operation, and MM_S and MM_G are the molecular weights of sucrose and glucose, respectively.

In literature detailing evaporator investigations conducted in Australia, Rackemann and Broadfoot (2016) used the Purchase equation (Purchase *et al.*, 1987) as shown in Equation 14 to estimate SIL:

$$SIL = \left[\left(\frac{G}{S}\right)_{out} - \left(\frac{G}{S}\right)_{in} \right] \times \frac{MM_S}{MM_G} \dots \text{Equation 14}$$

All the analytes used in Equations 13 and 14 have an associated analytical precision. To establish if Equation 13 is a more sensitive indicator of SIL than Equation 14, it is necessary to determine the analytical precision associated with SIL for each of these equations. The average ESJ and syrup concentrations used to estimate analytical precision (via a Monte Carlo simulation) were as follows:

- ESJ: 13°Bx, 85% gravity purity and 0.20% glucose; and
- Syrup: 65°Bx, 85% gravity purity and 1.00% glucose

The analytical precisions for Equations 14 and 15 were ± 1.33 and ± 1.44 , respectively. Thus, the Schöffler SIL equation is a slightly more sensitive measure of sucrose loss across the evaporator station than the Purchase equation. It is important to note that both these equations assume that glucose is not destroyed.

⁶ Personal communication with Dr S Nel, 2021.

Comparison between the SIL determined by Vukov and that determined by the Schäffler equation

According to the average results of 34 inversion loss trials conducted at the Gledhow sugar factory, Dairam *et al.* (2016) concluded that the Vukov model underestimated the SIL when compared to the measured SIL using the Schäffler equation. The overall SIL that was estimated using the Vukov model was approximately 8-15 times less than the measured SIL. Some of the potential causes for this difference are unpacked in the fishbone diagram shown in Figure 2. The major potential causes are: (1) the unreliability of the Vukov model in estimating the SIL for impure cane sugar solutions; (2) the incorrect juice retention time used for the Vukov model and during sampling for the Schäffler method and (3) the use of non-representative samples. Manual catch sampling typically does not account for the expected composition and flow changes in a raw sugar factory. A potential solution to mitigate these causes would be to perform well-designed laboratory experiments which would assist in checking the reliability of the Vukov model when using evaporator station process streams, and comparing SIL estimation methods (i.e. using the Vukov model and Schäffler method) by eliminating/reducing the impact of juice/syrup retention time and sample representation on the estimated SIL (provided that there are reliable measures and controls for temperature and pH, and that good mixing and sampling techniques are utilised).

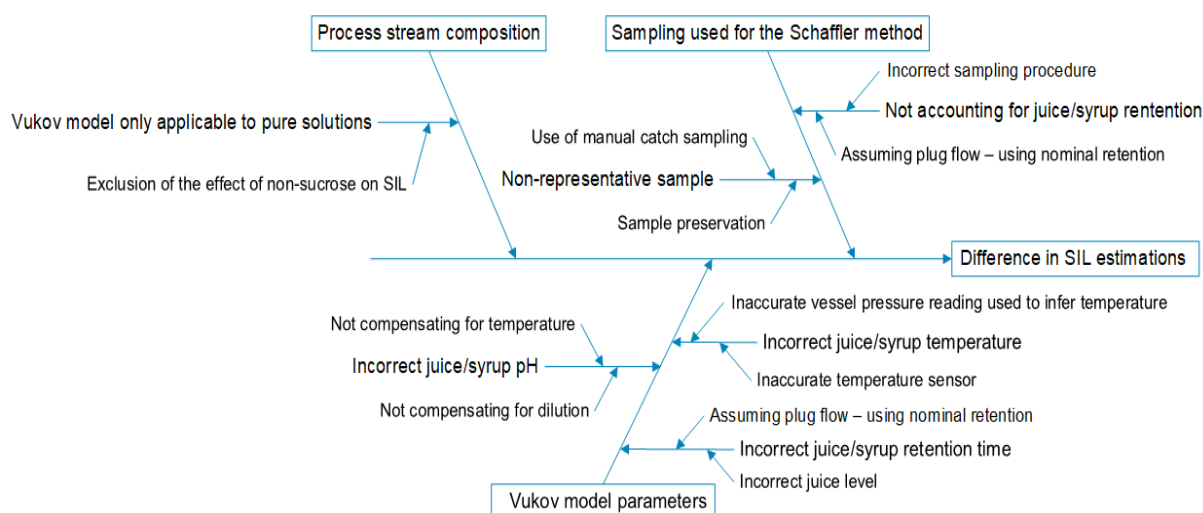


Figure 2. Root cause assessment for the difference between the Vukov and Schäffler SIL estimations

Conclusions

In summary,

- the rate of sucrose inversion in aqueous solutions depends on the sucrose concentration, the H^+ concentration (pH), the temperature of the solution, the OH^- concentration and the concentration of salts. Most sugar technologists (Rein, 2007; Schäffler *et al.*, 1985; Purchase *et al.*, 1987) have ignored the effect of OH^- ions, particularly for the evaporator station, as the conditions are generally acidic. Although the effect of salt concentration on the hydrolysis of sucrose has also been ignored, which is not justified considering the appreciable levels of cations and anions present in sugarcane solutions.

- A review of the numerical models for estimating SIL revealed that the Vukov (1965) and Parker (1967) acid hydrolysis models are commonly referred to in literature to determine the sucrose hydrolysis rate constant, with the former being the preferred choice. However, both models suffer from the drawback of being based on the kinetic work performed on pure sucrose solutions as opposed to sugar factory process streams (i.e. sugarcane juice/syrup/molasses). Furthermore, the Parker model is limited to a maximum temperature of 85°C whereas the Vukov model may be utilised up to a temperature of 130°C. A comparison of the Vukov and Parker models at 25°Bx and 70°Bx, at a pH range of 4 to 6 and a temperature range of 50 to 130°C concluded that the Parker model predicts a substantially lower sucrose loss than that predicted by the Vukov model.
- The Vukov model may be used for a brix range of 0 to 72.5°Bx, a pH range of 1.0 to 6.5 and a temperature range of 20 to 130°C, which makes the model suitable for use across a typical South African evaporator station. However, the pH of the solution should be measured at the operating temperature. A correlation was developed by Schäffler (1987a) to determine the pH of raw sugar factory process streams (i.e. sugarcane juices and syrups) at temperatures higher than 25°C. In Schäffler's (1987a) investigation, only two samples were studied at extreme temperatures (about 125°C). Some literature suggests that the Vukov model underestimates the SIL measured across a raw sugar factory evaporator station compared to the analytical measures of SIL. Reasons for this underestimation include the inaccurate estimation of model parameters, such as the juice/syrup retention time.

Indirect measures of SIL:

- Chemical markers: the chemical markers that may be used to gauge the extent of the sucrose inversion loss include $\Delta(S/B)$, $\Delta(S/Cl)$, $\Delta(G/B)$, $\Delta(G/Cl)$, $\Delta(G/S)$, $\Delta(F/B)$, $\Delta(F/Cl)$, $\Delta(F/S)$ and $\Delta(F+G/S)$. Given that all South African sugar factory laboratories are equipped with the SMRI-NIRS technology, and given the current capability of the technology, all of these chemical markers can be determined, except for those markers referenced against chloride. However, Schäffler *et al.* (1985) showed that either chloride or brix may be utilised as the reference chemical marker.
- Sensitivity of the chemical markers: Assuming that a sucrose loss of $\geq 1\%$ across the evaporator station is unacceptable, the chemical marker should at least be able to detect a loss of this order. The most sensitive SMRI-NIRS chemical markers, in descending order, were determined to be:

$$\Delta(F+G/S) > \Delta(F/B) \approx \Delta(F/S) > \Delta(G/S) \approx \Delta(G/B) > \Delta(S/B)$$

- The gravity purity difference, or $\Delta(S/B)$, is regarded as the least sensitive chemical marker as it can only detect sucrose losses greater than 3.4% across the evaporator station.
- Raw sugar factory evaporator stations typically operate at a pH that ranges from 5.9 (ESJ) to 5.7 (virgin syrup) at the typical operating temperature range (120 to 59°C); hence, they generally operate at slightly acidic conditions. Under acidic conditions, fructose is regarded as being more labile than glucose (Mauch, 1971; Schäffler, 1984; Wong Sak Hoi and Tse Chi Shum, 1996). In addition, Schäffler *et al.* (1985) used the F/G profile to show that fructose is preferentially destroyed compared to glucose under typical evaporator station process conditions. It is also unlikely that the common polysaccharides (*viz.* starch and dextran) present in sugarcane process streams would hydrolyse to glucose across the evaporator station. Therefore, $\Delta(G/B)$ and $\Delta(G/S)$ may be

regarded as the most sensitive and reliable indicators of SIL. These indicators can comfortably detect evaporator station sucrose losses $\geq 1.5\%$.

Direct measures of SIL:

- Calculation methods: The direct methods of calculating SIL include the use of the Schäffler *et al.* (1985) and Purchase *et al.* (1987) equations, which utilise the $\Delta(G/B)$ and $\Delta(G/S)$ ratios, respectively.
- Sensitivity of the SIL calculation method: The analytical precision of the Schäffler and Purchase equations were determined to be ± 1.33 and ± 1.44 , respectively; hence, the SIL calculated using the Schäffler equation is a more sensitive direct measure of SIL than the Purchase equation.

Differences between the SIL estimated by the Vukov model and Schäffler method:

- The overall SIL that was estimated using the Vukov model was approximately 8-15 times less than the measured SIL, using the Schaffler equation (Dairam *et al.*, 2016).
- The major potential causes for the above-mentioned difference included the unreliability of the Vukov model in estimating the SIL for impure cane sugar solutions, the inaccurate estimation of the juice/syrup retention time and its impact on the Vukov prediction, as well as the sampling performed as part of the Schäffler method.

Future work

- There is a need to compare the SIL estimated by the Vukov model to the direct measures of SIL (i.e. using the Schäffler and Purchase equations). The comparison should be performed using impure sucrose solutions, preferably raw sugar factory process streams. This comparison will assist in understanding the predictive strength of the Vukov model for impure cane sugar solutions. This may be achieved by well-designed laboratory experiments.
- The pH correlation determined by Schäffler (1987) should be verified with a special focus on the high temperature range (85 to 120°C). Furthermore, if practically possible, it would be ideal to extend the correlation to massecuites and molasses.
- For completeness, an empirical check should be performed to verify whether the polysaccharides present in sugarcane juice contribute to the formation of glucose across a raw sugar evaporator station as this review only focused on starch and dextran.

Acknowledgements

The authors acknowledge and sincerely offer gratitude to Steve Davis and Dr Sanet Nel for their contributions and support.

References

- Anon (2012a). SMRI Ten-Week Course in Sugar Engineering: *Factory performance calculations*. SMRI, Durban.
- Anon (2012b). SMRI Ten-Week Course in Sugar Engineering: *Evaporation*. SMRI, Durban.

- Anon (2012c). SMRI Ten-Week Course in Sugar Engineering: *Chemistry of cane juice*. SMRI, Durban.
- Anon (2019a). [https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_\(Physical_and_Theoretical_Chemistry\)/Kinetics/Reaction_Rates/First-Order_Reactions](https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Kinetics/Reaction_Rates/First-Order_Reactions), accessed 24 December 2019.
- Anon (2019b). <https://www.westlab.com/blog/2017/11/15/how-does-temperature-affect-ph>, accessed 24 December 2019.
- Anon (2019c). [https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_\(Physical_and_Theoretical_Chemistry\)/Kinetics/Modeling_Reaction_Kinetics/Temperature_Dependence_of_Reaction_Rates/The_Arrhenius_Law/Arrhenius_Equation](https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Kinetics/Modeling_Reaction_Kinetics/Temperature_Dependence_of_Reaction_Rates/The_Arrhenius_Law/Arrhenius_Equation), accessed 24 December 2019.
- Anon (2021). [What is dextran? | TdB Labs](#), accessed 6 May 2021.
- Barker B (2012). Ubombo evaporator inversion loss survey - November 2011. *Sugar Milling Research Institute NPC Technical Note No. 03/12* (restricted circulation), 27 January, 7 pp.
- Barker B and Madho S (2008). Evaporator inversion loss and tracer test at Maidstone. *Sugar Milling Research Institute NPC Technical Note No. 01/08* (restricted circulation), 16 January, 9 pp.
- Bednarska KA (2015). Kinetic modelling of enzymatic starch hydrolysis. *PhD thesis*. Wageningen University, Netherlands, pp. 3-4.
- Dairam N, Ramaru R, Ngema S, Sutar N and Madho S (2016). Sucrose losses across the Gledhow evaporators determined using NIRS predictions. *Proc S Afr Sug Technol Ass* 89: 391-405.
- Davis SB (1995). Inversion survey of the Noodsberg evaporator station. *Sugar Milling Research Institute NPC Technical Note No. 06/95*, 8 March, 9 pp (restricted circulation).
- Hamdy MK, van Winkle Q, Stahly GL, Weiser HH and Birkeland JM (1956). Factors affecting the degradation processes for dextran. *The Ohio Journal of Science* 56: 41-51.
- Honig P (1953). *Principles of Sugar Technology*. Vol. 1. Elsevier Publishing Company, Amsterdam.
- Honig P (1959). *Principles of Sugar Technology*. Vol. 2. Elsevier Publishing Company, Amsterdam.
- Honig P (1963). *Principles of Sugar Technology*. Vol. 3. Elsevier Publishing Company, Amsterdam.
- Kolusheva T and Marinova A (2007). A study of the optimal conditions for starch hydrolysis through thermostable α -amylase. *Journal of the University of Chemical Technology and Metallurgy* 42: 93-96.

- Madho S (2011). Sezela evaporator inversion loss survey. *Sugar Milling Research Institute NPC Technical Note No. 20/11* (restricted circulation), 28 October, 5 pp.
- Mauch W (1971). The chemical properties of sucrose. *Sugar Technol Rev* 1: 249-266.
- Mega TL and van Etten RL (1988). The oxygen-18 isotope shift in carbon-13 nuclear magnetic resonance spectroscopy. XII: Position of bond cleavage in the acid-catalysed hydrolysis of sucrose. *J Amer Chem Soc* 110(19): 6372-6376.
- Parker KJ (1967). *Sugar industry abstracts*. Tate and Lyle Ltd. Research Centre, England.
- Parker KJ (1970). Chemical problems in the sucrose industry. *La Sucrierie Belge* 89: 119-126.
- Pillay V (2018). Method uncertainty 2018. <https://smri.sharepoint.com/:x/s/teams/Quality/Ee8oLtMOcK9ErqvFKW1Ku7gBWfT4FZEvX4K1TyTThoisNA?e=LQD1ts>, Accessed on 4 February 2018 (internal Sugar Milling Research Institute NPC file).
- Purchase BS, Day-Lewis CMJ and Schäffler KJ (1987). A comparative study of sucrose degradation in different evaporators. *Proc S Afr Sug Technol Ass* 61: 8-13.
- Rackemann DW and Broadfoot R (2016). Evaluation of sucrose loss in evaporators for different processing configurations. *Proc Int Soc Sugar Cane Technol* 29: 267-271.
- Rackemann D and Marasinghege C (2023). Understanding and minimising the impacts of non-sucrose constituents of sugarcane juice on juice degradation during evaporation. *Proc Int Soc Sug Cane Technol* 31: 805-817.
- Rahiman SN and Balkissoon, S (2017). NIRS inversion loss toolkit study: Validation of the Vukov model. Presentation delivered at SMRI (internal meeting). https://smri.sharepoint.com/:p/s/research/1B-10/Ef66ZhaFMApCvu1R7h741_4BUueMexJlwwWEwB8CqU0GFA?e=4kJU1F, 21 August 2017 (internal Sugar Milling Research Institute NPC file).
- Rahiman S, Weyer S, Visram K and Davis SB (2019). A survey of a juice preparation station using SMRI-NIRS. *Sugar Milling Research Institute NPC Technical Report No. 2306*, 10 September (restricted circulation): 26 pp.
- Rein PW (2007). *Cane Sugar Engineering*. Dr Albert Bartens, 2nd edition, Berlin.
- Sapranov AR and Koltschewa RA (1975). Die kinetik der Saccharosezersetzung und die von pH Temperatur Abhangige Hexose. *Proc CITS*: 195-207.
- Schäffler KJ (1984). A review of the published kinetic work on estimating sucrose and invert losses in hot sugar solutions. *Sugar Milling Research Institute NPC Internal Report* 1/84, 3 January (restricted circulation), 14 pp.
- Schäffler KJ (1987a). Estimation of pH of sugar cane juices at high temperatures. *Proc S Afr Sug Technol Ass* 61: 14-17.
- Schäffler KJ (1987b). Possible inversion losses in the Illovo evaporator. *Sugar Milling Research Institute NPC Technical Note No. 29/87*, 17 August, 2 pp (restricted circulation).

Schäffler KJ (1988). Monitoring inversion losses in the Maidstone and Amatikulu evaporators. *Sugar Milling Research Institute NPC Technical Note* No. 11/88, 31 March, 6 pp (restricted circulation).

Schäffler KJ, Muzzell DJ and Schorn PM (1985). An evaluation of sucrose inversion and monosaccharide degradation across evaporation at Darnall mill. *Proc S Afr Sug Technol Ass* 59: 73-78.

Vukov K (1965). Kinetic aspects of sucrose hydrolysis. *Int Sug J* 67: 172-175.

Wong Sak Hoi L and Tse Chi Shum S (1996). Estimation of sucrose inversion in evaporators. *Proc S Afr Sug Technol Ass* 70: 23.