REFEREED PAPER

MODELLING THE FLOW OF CANE CONSTITUENTS IN THE MILLING PROCESS

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Abstract

A model has been developed to track the flow of cane constituents through the milling process. While previous models have tracked the flow of fibre, brix and water through the process, this model tracks the soluble and insoluble solid cane components using modelling theory and experiment data, assisting in further understanding the flow of constituents into mixed juice and final bagasse. The work provided an opportunity to understand the factors which affect the distribution of the cane constituents in juice and bagasse. Application of the model should lead to improvements in the overall performance of the milling train.

Keywords: soluble solids, insoluble solids, impurities, mass balance model, juice, bagasse

Introduction

Over the years, sugarcane processing researchers have developed models to understand and improve the milling process. Thaval and Kent (2012) reviewed the major developments and presented an enhanced mill extraction model to predict extraction performance of the milling process. The enhanced model tracks the flow of brix, moisture and fibre through the milling train and the distribution of these components in juice and bagasse.

The soluble and insoluble impurities in cane affect the performance of the milling train and further processing of bagasse and juice. In the Thaval and Kent (2012) extraction model, all the soluble solids are termed as brix and all the insoluble solids are termed as fibre. To date, no efficient model has been developed to track the soluble and insoluble impurities in the milling process. Specific impurities in cane, mixed juice and final bagasse have been reported by authors worldwide, but none have reported a holistic approach to address all major impurities.

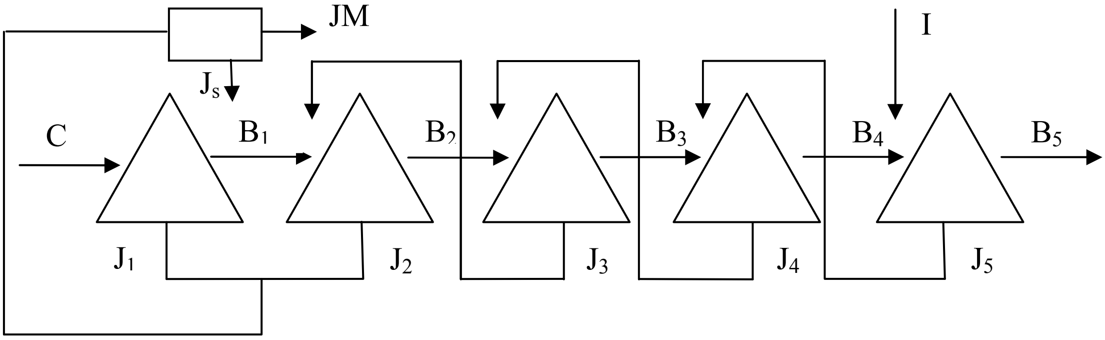
In this paper, a model is described to determine the flow of cane constituents through the milling process. The focus of this model is to break down the soluble solids (brix) into pol and soluble impurities and insoluble solids (fibre) into true fibre and mud solids impurities and determine the flow of these components through the milling process. Ultimately, this model is intended for use in a 'whole of factory' model and will provide the correct constituents in mixed juice and final bagasse as inputs to the downstream station models.

Model framework

As an extension to the model introduced by Thaval and Kent (2012), the components model follows the same modelling framework. A milling train model was constructed from a series of milling unit models and a juice screen model. The links between the milling units and juice screen follow mass balance fundamentals.

The milling unit model uses four parameters to determine how the fibre, brix and moisture inputs to the milling unit are divided between bagasse and expressed juice. These parameters are filling ratio and reabsorption factor to describe the separation of juice from bagasse, imbibition coefficient to describe the separation of brix from juice and separation efficiency to describe the separation of fibre from juice. The juice screen model used a juice screen separation efficiency parameter to describe the separation of fibre from juice and assumes that the brix fraction of juice in mixed juice and the return stream from the juice screen are the same.

Figure 1 shows how the milling unit and juice screen models fit together into a full milling train model. The following mass balance equations describe the flows between model items. In the equations, the general form of a parameter is q_{pc}, where q is a quantity, p is a product, and c is a component. In Figure 1, the legend shows all the products used in this model.



Legend:

C	Cane
I	Imbibition
B	Bagasse streams
J	Expressed juice streams
J_s	Return stream from juice screen
JM	Mixed juice

Figure 1. Milling train mass flows.

$$\dot{m}_C = \dot{m}_{J1} + \dot{m}_{B1} \quad (1)$$

$$\dot{m}_{B1} + \dot{m}_{Js} + \dot{m}_{J3} = \dot{m}_{B2} + \dot{m}_{J2} \quad (2)$$

$$\dot{m}_{B2} + \dot{m}_{J4} = \dot{m}_{B3} + \dot{m}_{J3} \quad (3)$$

$$\dot{m}_{B3} + \dot{m}_{J5} = \dot{m}_{B4} + \dot{m}_{J4} \quad (4)$$

$$\dot{m}_{B4} + \dot{m}_I = \dot{m}_{B5} + \dot{m}_{J5} \quad (5)$$

$$\dot{m}_C + \dot{m}_I = \dot{m}_{JM} + \dot{m}_{B5} \quad (6)$$

where $\dot{m}_p$ is the mass flow rate (kg/s) of any product p listed in Figure 1.

Mass must be conserved across each milling unit and across the entire milling train. Although equations 1 to 6 show only total mass flows (and hence the parameters do not show a component such as fibre), they also apply to fibre mass flow, brix mass flow and to the mass flow of components of those flows.

Soluble solids model

Introductory remarks

The soluble solids (brix) in cane include around 80-90% sucrose and 10-20% impurities. These soluble impurities are further classified as reducing sugars, organic matter, inorganic compounds and nitrogenous bodies (Walford, 1996). In this model, the soluble solids have been divided into sucrose, reducing sugars, ash, proteins and the remainder. This section discusses methodologies to calculate these soluble solid component flows.

Sucrose

There have been several efforts to model the sucrose extraction of a milling train. Lionett (1981) proposed an empirical equation to determine the sucrose extraction from brix extraction based on mixed juice purity and cane purity. Wienese (1995) attempted to extend his brix extraction model to determine the sucrose extraction of milling tandems and diffusers. The equation was of a general form based on Lionett's equation, consisting of three constants determined from three ideal conditions. Wienese (1994) had a similar empirical equation to determine sucrose extraction from brix extraction. The equations developed by Lionett and Wienese are empirical equations used to determine the sucrose extraction of the entire milling train, but cannot be applied on a milling unit basis.

For the purpose of the sucrose model here, a more appropriate model for sucrose was developed by the Sugar Research Institute in the early 1980s. This approach is based on the concept of a purity ratio to determine the pol content of bagasse from a milling unit from the brix content. The purity ratio was defined as:

$$ZR_n = \frac{Z_{Bn}}{Z_C} \tag{7}$$

where ZR_n is the purity ratio of the n^{th} mill,
Z_{Bn} is the purity of bagasse from the n^{th} mill,
Z_C is the purity of cane.

The purity ratio can be calculated from cane and bagasse analysis data and assumed to be constant for the prediction of pol in bagasse from brix in bagasse. Once the fibre, brix and moisture of the bagasse from each milling unit have been predicted using a model such as that presented by Thaval and Kent (2012), the purity ratio concept can be used to calculate the pol or sucrose component of the brix of each bagasse.

Firstly, the purity of the bagasse is calculated by rearranging equation (7):

$$Z_{Bn} = ZR_n \times Z_C \tag{8}$$

The pol of the bagasse is determined from the equation:

$$P_{BnP} = Z_{Bn} \times P_{BnB} \tag{9}$$

where P_{BnP} is the pol% bagasse of the n^{th} mill,
P_{BnB} is the brix% bagasse of the n^{th} mill.

The mass flow of pol in bagasse is determined from the equation:

$$\dot{m}_{BnP} = P_{BnP} \times \dot{m}_{Bn} \tag{10}$$

where $\dot{m}_{BnP}$ is mass flow of pol in bagasse of n^{th} mill,
$\dot{m}_{Bn}$ is total mass flow in bagasse of n^{th} mill.

Equations 1 to 6 can be applied to the mass flow of pol in the milling train. While the mass flow of pol in the bagasse streams has been determined, the mass flow of pol in the expressed juice streams, return stream from the juice screen and mixed juice stream are unknown in the model. Hence, there are seven unknowns and only six equations. To solve the model, the approach reported by Loubser (2004) was adopted and it was assumed that the purity of return stream from the juice screen (cush return) and the purity of mixed juice are the same.

Reducing sugars

The most abundant non-sucrose components in cane are the monosaccharides; glucose and fructose, also known as reducing sugars (Rein, 2007). The major concern with modelling reducing sugars is the potential for inversion of the sucrose into reducing sugars. The amount of inversion that occurs is not well known. van der Pol and Alexander (1955) reported that the reason for inversion of sucrose is the destruction of sucrose by enzymes. These authors stated that the possible losses by the inversion are due to the combined effect of temperature and pH, which are small under normal operating conditions and can be neglected. Rein (2007) supported this view.

Fernandes (2003) proposed an empirical equation to determine the reducing sugars in mixed juice from mixed juice purity, and reducing sugars in cane from mixed juice reducing sugars and fibre content in cane. The validity of this model was tested by conducting a 3^7 numerical factorial experiment to study the effect of individual factors on reducing sugars levels. In particular, the level of inversion of sucrose to reducing sugars and the conditions for that inversion were of interest. To conduct this assessment an invert ratio (IR) was defined as the ratio of reducing sugars to sucrose. The parameters and their levels examined in the experiment are presented in Table 1.

Table 1. Parameters and their levels studied to determine the effect on invert ratio.

Parameter	Symbol	Levels
Cane fibre content (%)	P_{CF}	10, 15, 20
Ratio of cane pol content to cane fibre content	X_{CP}	0.6, 0.8, 1.0
Cane purity (%)	Z_C	80, 85, 90
Total pol extraction (%)	E_P	90, 94, 97
Final bagasse purity ratio	ZR	0.60, 0.75, 0.90
Final bagasse moisture content (%)	P_{BnW}	45, 50, 55
Added water % fibre	X_I	200, 250, 300

Based on the defined experimental parameters, the purity of mixed juice was calculated using conventional mass balance equations.

The reducing sugars content of mixed juice was determined using Fernandes (2003) equation:

$$P_{JMRS} = 3.641 - 0.0343 \times Z_{JM} \quad (11)$$

where P_{JMRS} is reducing sugars% mixed juice,
Z_{JM} is purity of mixed juice.

The reducing sugars content of cane was determined using Fernandes (2003) equation:

$$P_{CRS} = P_{JMRS} \times (1 - 0.01 \times P_{CF}) \times (1.0313 - 0.00575 \times P_{CF}) \quad (12)$$

where P_{CRS} is reducing sugars% cane,
P_{CF} is fibre% cane.

Invert ratios were then calculated for cane and mixed juice and the ratio of the invert ratio for mixed juice to the invert ratio for cane was calculated. Figure 2 shows the results of the experiment. Along the horizontal axis are the experimental factors. Each factor level is presented on a vertical bar for the factor. The value for the ratio of the invert ratio for mixed juice to the invert ratio for cane at each factor level represents the average result for all tests of the experiment conducted at that factor level. For example, the 20% cane fibre content level shows an average ratio of about 1.14, representing the average result for the one-third of the tests conducted at that factor level.

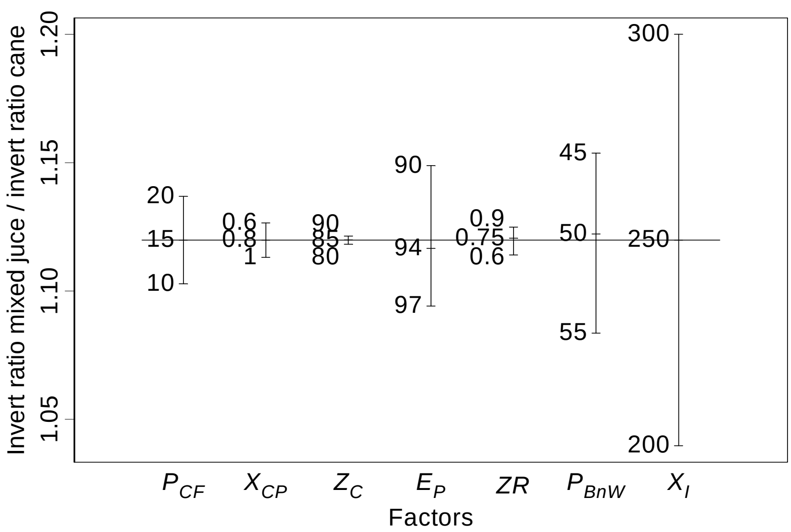


Figure 2. Exploration of the invert ratio model.

The results show that the ratio of cane pol content to the cane fibre content (X_{CP}), purity of cane (Z_C) and purity ratio of the final bagasse (ZR) were the factors with the least impact and imbibition level (X_I), moisture content of bagasse (P_{BnW}) and pol extraction of the mill (E_P) were the factors with the highest impact on the ratio. It seems unlikely that three of the four factors associated with the sugar content would have less impact than the factors associated with the fibre and moisture contents, indicating some doubt that this model accurately represents the flow of reducing sugars from cane into mixed juice. If the model was assumed correct, the fact that the ratio exceeds 1.0 implies that sucrose inversion is occurring at a significant level in the milling process. This conclusion is contrary to that of van der Pol and Alexander (1955) and Rein (2007). To resolve these contradictory conclusions, an experiment was done to measure the reducing sugars in the milling process.

The experimental investigation was undertaken at Isis sugar mill in Australia. Samples of shredded cane, first expressed juice and mixed juice were collected while processing large rakes of cane (continuous supply of cane in rail wagons from a single field) to avoid mixing of cane supplies. The first expressed juice and mixed juice samples were filtered and frozen to avoid degradation of the sugars. The shredded cane sample was processed quickly to measure the moisture content and the pol and brix content by disintegration. The disintegrator extract was collected and stored along with the first expressed juice and mixed juice samples. In total, eight different rakes of cane were sampled in this way. Method 5 of the BSES laboratory manual (Bureau of Sugar Experiment Stations, 2001) was followed in the sampling and mixing of shredded cane. All juices were stored at -20°C and thawed prior to analysis.

In the laboratory, the brix of samples was measured at ambient room temperature using a Bellingham and Stanley RFM 342 Refractometer. The separation and quantification of sugars, in duplicate, was conducted by high performance ion chromatography coupled with pulse amperometric detection (HPIC_PAD) based on the ICUMSA method GS7/8/7-24. Analyses were carried out on a Waters HPIC_PAD system coupled to a Waters 2465 electrochemical detector (Thai and Doherty, 2011). Table 2 shows the sugar analysis results from the Isis experiment. Note that reducing sugars (RS) has been defined as the sum of glucose and fructose.

Table 2. Sugar analysis results from the Isis experiment.

Sample	Stream	Sugar % cane			$\left(\frac{RS}{Sucrose}\right)$
		Glucose	Fructose	Sucrose	
1	Cane	0.63	0.57	7.28	0.1706
	FEJ	0.76	1.60	19.17	0.1633
	JM	1.61	1.15	16.55	0.1657
2	Cane	0.36	0.40	7.78	0.0986
	FEJ	0.44	0.47	21.51	0.0930
	JM	0.38	0.42	15.00	0.0933
3	Cane	0.25	0.29	9.74	0.0558
	FEJ	0.59	0.64	23.56	0.0521
	JM	0.49	0.53	15.56	0.0514
4	Cane	0.47	0.50	9.07	0.1003
	FEJ	0.97	1.48	22.36	0.0939
	JM	0.66	0.98	12.61	0.0977
5	Cane	0.84	0.87	12.61	0.1335
	FEJ	0.33	0.29	20.07	0.1244
	JM	1.25	1.24	17.35	0.1268
6	Cane	0.71	0.53	10.63	0.1159
	FEJ	1.12	1.25	22.20	0.1072
	JM	0.86	0.99	14.98	0.1235
7	Cane	0.84	0.66	8.77	0.1710
	FEJ	1.67	1.43	18.81	0.1573
	JM	1.30	1.00	14.07	0.1639
8	Cane	0.66	0.54	8.54	0.1255
	FEJ	1.27	1.23	20.07	0.1282
	JM	1.04	0.96	17.30	0.1159

An analysis of variance found no statistically significant difference between the invert RS over sucrose ratios of cane and mixed juice. It is noted, however, that the experiment was conducted with an added water temperature of 60°C, a low value by Australian standards.

Vukov (1965) proposed a formula to determine the rate of hydrolysis (inversion) for solutions with sugar concentration between 0 and 0.9 g/ml, temperature between 20 and 130°C and pH between 1 and 6.5. The calculated reaction rate constant (k_a) for each mill in the milling train is shown in Table 3. These values of rate constant were calculated by using the following data. Kent (2010a) reported typical temperatures of mill juices. The pH of the juices was assumed to be a constant 5.5. Russell (1968) provided a formula to calculate the density of juice and the sucrose concentration was obtained from the brix (Bureau of Sugar Experiment Stations, 2001).

While it is not easy to convert a reaction rate constant to a likelihood of inversion, the results show that inversion is much more likely to occur in #4 and #5 mills than earlier in the train, due to an increase in the reaction rate constant of two orders of magnitude. Since only about 10% of the sucrose is extracted from #4 and #5 mills and the time that the juice is held at this temperature is at most about two minutes, it seems likely that inversion is limited to a very small fraction of 10% sucrose.

Table 3. Rate of hydrolysis in mill products.

Temp (°C)	pH	Density (g/ml)	Sucrose conc. (g/ml)	Log k_a	k_a (min^{-1})	Stream
98	–	–	–	–	–	Added water
30	5.5	1.068	0.196	-7.36	4.37×10^{-8}	#1 mill
50	5.5	1.053	0.132	-6.23	5.88×10^{-8}	#2 mill
60	5.5	1.042	0.071	-5.65	2.24×10^{-8}	#3 mill
69	5.5	1.034	0.043	-5.18	6.61×10^{-6}	#4 mill
77	5.5	1.024	0.022	-4.79	1.62×10^{-5}	#5 mill

Considering the available evidence, it is concluded that the inversion of sucrose in the milling process is negligible and the RS over sucrose ratio can be assumed constant for all mills in the milling train.

The RS over sucrose ratio or invert ratio can be calculated from cane analysis:

$$IR = \frac{P_{CRS}}{P_{CP}} \tag{13}$$

where IR is the invert ratio,
P_{CRS} is the reducing sugars% cane,
P_{CP} is the pol% cane.

The reducing sugars in the bagasse streams can be determined from:

$$P_{BnRS} = IR \times P_{BnP} \tag{14}$$

where P_{BnRS} is the reducing sugars content in bagasse of the n^{th} mill,
P_{BnP} is the pol content in bagasse of the n^{th} mill.

As for the sucrose mass balance described above, the mass flow equations 1 to 6, along with the assumption that the invert ratio of the return stream from the juice screen is the same as the cane invert ratio, can be applied to model the flow of reducing sugars through the milling process.

Soluble ash

The inorganic component of brix in cane is often reported by the method from which it is analysed (involving combustion of all organic material): ash. Soluble ash consists of the inorganic salts present in the cane.

Wienese and Reid (1997) developed an ash mass balance model based on the total ash in cane, total ash in bagasse, and soluble ash in mixed juice, assuming the extraction of soluble ash is equal to brix extraction. Wienese and Reid (1997) did not provide any evidence to support the assumption that soluble ash extraction and brix extraction could be equated.

In Australian factories, soluble ash in mixed juice and final bagasse are not measured on a routine basis. Some data, however, was collected during the Isis experiment described above. Table 4 shows the ash (and proteins) analysis results for cane, first expressed juice and mixed juice. The soluble ash was measured by Method 26, *Determination of ash in sugar products by the single sulphation method* (Bureau of Sugar Experiment Stations, 2001).

Table 4. Soluble ash and proteins in mill products.

Sample	Stream	S.ash (%)	S.ash/Brix ($x10^{-2}$)	Proteins (%) ($x10^{-3}$)	Proteins/Brix ($x10^{-4}$)
1	Cane	0.58	2.92	6.39	4.80
	FEJ	0.48	2.53	9.30	4.73
	JM	0.43	3.09	7.40	8.73
2	Cane	0.60	2.94	5.99	4.19
	FEJ	0.44	2.21	3.33	1.42
	JM	0.33	2.17	8.30	5.33
3	Cane	0.64	3.17	3.80	0.21
	FEJ	0.46	3.50	3.60	1.88
	JM	0.28	3.43	0.60	0.43
4	Cane	0.94	3.07	8.87	4.69
	FEJ	0.71	3.52	6.60	3.25
	JM	0.56	4.20	8.40	6.25
5	Cane	0.72	3.54	6.27	7.97
	FEJ	0.66	4.36	3.00	1.97
	JM	0.36	2.59	3.40	9.48
6	Cane	0.59	4.46	7.53	5.65
	FEJ	0.35	1.70	5.22	5.14
	JM	0.24	1.63	2.90	1.96
7	Cane	0.57	4.36	3.75	3.00
	FEJ	0.30	1.60	4.20	2.20
	JM	0.35	5.16	8.30	1.25
8	Cane	0.52	3.06	5.33	3.11
	FEJ	0.43	2.56	4.90	2.89
	JM	0.33	2.68	1.80	1.46

Table 4 also shows the soluble ash to brix ratio of the mill products. An analysis of variance did not identify any statistically significant differences between the ash on brix ratios of the three streams. As a result, the flow of soluble ash is modelled assuming the ash on brix ratio is constant for all the bagasse streams in the milling process, in agreement with the implied assumption of equal soluble ash and brix extraction made by Wienese and Reid (1997):

$$R_{AB} = \frac{P_{CAx}}{P_{CB}} \tag{15}$$

where P_{CAx} is % soluble ash in cane,
P_{CB} is % brix in cane,
R_{AB} is ash on brix ratio.

Applying the mass balance equations 1 to 6 and assuming the ash on brix ratio is the same for the return stream from the juice screen; the model can be used to complete a mass balance of soluble ash.

Proteins

Proteins are present in amino acids in peptide linkages. They account for 0.1 to 0.2% of dry solids in cane (Martin, 1958). Wiggins (1958) reported that non-sugars in cane consist of 9% proteins, 9.5% amino acids and 15.5% amino acids amides.

Protein content was measured in the Isis experiment and the results are reported in Table 4. The colorimetric detection and quantification of protein in the samples was conducted using the bicinchonic acid (BCA) Protein Assay Kit (Pierce, Bonn, Germany); 25 µL sample/200 µL BCA working reagent; 37°C for 30 min; 562 nm, based on the manufacturer's instructions. The quantification (in triplicate) of protein was carried out on a Beckman AD 200 UV/VIS plate reader (Thai and Doherty, 2011).

Modelling the flow of proteins raises the issue of where in the sugar production process proteins are precipitated (Kent, 2010b). When they are precipitated, the proteins transfer from a component of brix to a component of insoluble solids. The effect of temperature on precipitation and dissolution of proteins was explored by Macritchie (1973). Macritchie measured the concentration of BSA (an animal protein) in the dilute protein phase as a function of total concentration at temperatures of 45, 50, 55, 60 and 65°C. It was found that for all temperatures, no significant precipitation of BSA was recorded.

The results obtained by Macritchie (1973) could not be confidently transferred to sugarcane proteins. As a result, an experiment was conducted to study the effect of temperature on protein precipitation in first expressed juice, using samples from the Isis experiment. The experiment was conducted using the Bio-Rad Protein Assay. The samples in triplicate were exposed for 1 minute at temperatures of 20, 30, 40, 50, 60, 70 and 80°C. Figure 3 shows the effect of temperature (°C) on protein concentration (mg/ml) in solution. By inference, proteins not in solution have been precipitated.

Sample 2-FEJ had the highest protein content and shows a substantial reduction in protein concentration at temperatures over 60°C. The two other samples with lower protein contents did not show a substantial reduction in protein concentration in the temperature range explored.

To consider the likelihood of protein precipitation in the milling train, the temperature data from five-mill milling trains reported by Kent (2010a) were used (as in the earlier reducing sugars discussion). Even with the highest temperature added water, the bagasse temperature exceeded 60°C from #4 and #5 mills only. Since only about 10% of the brix is extracted from #4 and #5 mills and at most only about half of the proteins in that brix are precipitated, it seems likely that no more than 5% of the proteins in cane are precipitated in the milling train. Consequently, the assumption that proteins remain part of brix through the whole milling train seems adequate.

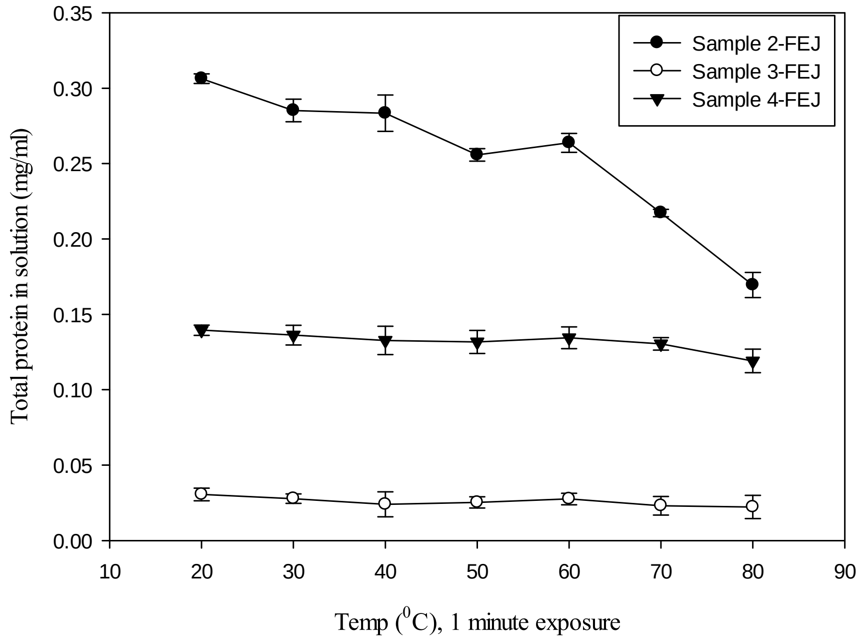


Figure 3. Effect of temperature on proteins concentration.

For modelling purposes, it was assumed that the ratio of proteins to brix remains constant throughout the milling process:

$$R_{Ap} = \frac{P_{Cp}}{P_{CB}} \quad (16)$$

where P_{Cp} is % proteins in cane,
P_{CB} is % brix in cane,
R_{Ap} is the protein on brix ratio.

Applying the mass balance equations 1 to 6 and assuming the protein on brix ratio is the same for the return stream from the juice screen, the model can be used to complete a mass balance of proteins.

Insoluble solids model

Introductory remarks

The insoluble solids, termed as cane fibre, account for 10-20% of the cane. The cane fibre includes about 80-90% of true fibre and 10-20% of mud solids. There are insoluble ash components in both true fibre and mud solids (Bureau of Sugar Experiment Stations, 2001).

An overall mass balance model

Kent (2010b) developed a model to determine bagasse production from an insoluble solids mass balance. The model tracked ash and non-ash components and true fibre and mud solids components of the insoluble solids but considered only the overall insoluble solids mass balance of the milling train and not the insoluble solids mass flows for the individual milling units. The Kent (2010b) model has been used as the basis of a method to determine the split of true fibre and mud solids into final bagasse and mixed juice. This section describes the methodology to calculate the insoluble solid component (true fibre and mud solids) flows.

The insoluble solids mass flow in cane is determined from:

$$\dot{m}_{CF} = P_{CF} \times \dot{m}_C \tag{17}$$

where $\dot{m}_{CF}$ is cane fibre rate,
$\dot{m}_C$ is cane rate,
P_{CF} is % fibre in cane.

Insoluble solids (fibre) content in cane and cane rate are both routine measurements at Australian sugar factories.

It is not common to measure either true fibre or mud solids in cane. The insoluble ash in cane, however, is routinely measured in some factories:

$$\dot{m}_{CAy} = P_{CAy} \times \dot{m}_C \tag{18}$$

where $\dot{m}_{CAy}$ is the mass flow of insoluble ash in cane,
P_{CAy} is % insoluble ash in cane.

Assuming that mud solids in cane is 100% ash, the true fibre and mud solids in cane are determined from:

$$\dot{m}_{C\hat{F}} = \left(\frac{\dot{m}_{CF} - \dot{m}_{CAy}}{1 - X_{C\hat{F}Ay}}\right) \tag{19}$$

$$\dot{m}_{CM} = \dot{m}_{CF} - \dot{m}_{C\hat{F}} \tag{20}$$

where $\dot{m}_{C\hat{F}}$ is mass flow of true fibre in cane,
$\dot{m}_{CM}$ is mass flow of mud solids in cane,
$X_{C\hat{F}Ay}$ is the fraction of insoluble ash in true fibre in cane.

As indicated by Kent (2010b), Muller *et al.* (1982) reported values of ash in cane of 0.13-0.36%. If the insoluble solids content in cane is assumed to be around 12-15%, the ash content of true fibre can be assumed to be 1.1-3.0%. The $\left(1 - X_{C\hat{F}Ay}\right)$ term refers to the non-ash component of true fibre. Since it was assumed that mud solids contain 100% ash, the non-ash component of mud solids is zero.

The insoluble ash in true fibre and mud solids in cane are calculated from:

$$m_{C\hat{F}Ay} = X_{C\hat{F}Ay} \times \dot{m}_{C\hat{F}} \tag{21}$$

$$\dot{m}_{CMAy} = \dot{m}_{CAy} - \dot{m}_{C\hat{F}Ay} \tag{22}$$

where $\dot{m}_{C\hat{F}Ay}$ is the mass flow of insoluble ash in true fibre in cane,
$\dot{m}_{CMAy}$ is the mass flow of insoluble ash in mud solids in cane.

Kent (2010b) developed an equation to determine the mass of insoluble solids in bagasse from an insoluble ash mass balance.

$$\dot{m}_{BF} = \left(\frac{\dot{m}_{CF} - \dot{m}_{CAy} - \dot{m}_{MF^*} + \dot{m}_{MAy}}{1 - \frac{(P_{BA} - P_{BAx})}{P_{BF}}} \right) \tag{23}$$

where $\dot{m}_{BF}$ is the mass of insoluble solids in bagasse,
$\dot{m}_{MF^*}$ is the equivalent mass of insoluble solids in mud (taking into account protein precipitation that occurs during the clarification process),
$\dot{m}_{MAy}$ is the mass of insoluble ash in mud,
P_{BA} is the percent total ash in bagasse,
P_{BAx} is the percent soluble ash in bagasse,
P_{BF} is the percent insoluble solids in bagasse.

Kent (2010b) presented equations to calculate the equivalent mass of insoluble solids in mud and the mass of insoluble ash in mud. The model of Kent (2010b) was extended to determine the true fibre and mud solids in bagasse.

The total ash in bagasse is measured in some Australian sugar factories. The mass of ash in bagasse can be calculated from:

$$\dot{m}_{BA} = P_{BA} \times \dot{m}_B \tag{24}$$

where $\dot{m}_{BA}$ is the mass flow of total ash in bagasse.
$\dot{m}_B$ is the total mass flow in bagasse.

The soluble ash in bagasse is calculated from the soluble solids model. The insoluble ash in bagasse can be calculated from:

$$\dot{m}_{BAy} = \dot{m}_{BA} - \dot{m}_{BAx} \tag{25}$$

where $\dot{m}_{BAy}$ is the mass flow of insoluble ash in bagasse,
$\dot{m}_{BAx}$ is the mass flow of soluble ash in bagasse.

The true fibre in bagasse can be calculated from:

$$\dot{m}_{B\hat{F}} = \frac{\dot{m}_{BF} - \dot{m}_{BAy}}{1 - X_{C\hat{F}Ay}} \tag{26}$$

where $\dot{m}_{B\hat{F}}$ is the mass flow of true fibre in bagasse,
$X_{C\hat{F}Ay}$ is the fraction of insoluble ash in true fibre in cane (which is assumed to be the same as the fraction of ash in true fibre in bagasse).

The mass flow of mud solids in mixed juice can be calculated from:

$$\dot{m}_{JMM} = \dot{m}_{CM} - \dot{m}_{BM} \tag{27}$$

where $\dot{m}_{JMM}$ is the mass flow of mud solids in mixed juice,
$\dot{m}_{CM}$ is the mass flow of mud solids in cane,
$\dot{m}_{BM}$ is the mass flow of mud solids in bagasse.

The ratio of mud solids in mixed juice to the mud solids in cane (M_{CJM}) can be calculated from:

$$M_{CJM} = \frac{\dot{m}_{JMM}}{\dot{m}_{CM}} \tag{28}$$

The model for a milling unit

In the mill extraction model presented by Thaval and Kent (2012), the separation efficiency defined the proportion of total insoluble solids that is expressed with the juice. The separation efficiency examples in the paper used fibre in juice measurements reported by Kent (2001). These fibre measurements were actually true fibre measurements and not total insoluble solids measurements. Consequently, the separation efficiencies calculated by Thaval and Kent (2012) relate more correctly to *true fibre* separation efficiencies.

Because of the need to separate true fibre and mud solids, there is a need for two separation efficiency terms for each mill. Since the existing measurements of fibre in juice are true fibre measurements, true fibre separation efficiency (S_{TFn} for the n^{th} mill) is defined as one of them. The separation efficiency for total insoluble solids is related to the true fibre separation efficiency by:

$$S_n = \frac{S_{TFn}}{F_{TF}} \tag{29}$$

where S_n is the separation efficiency of total insoluble solids,
S_{TFn} is the true fibre separation efficiency,
F_{TF} is the true fibre factor.

The true fibre factor is a single factor that is applied to the separation efficiency for all the milling units and the juice screen and provides a capability to ensure that mud solids are correctly distributed between final bagasse and mixed juice as discussed in the next section.

The model for the juice screen

Like the milling unit model, the juice screen model has to be able to distinguish between true fibre and mud solids. An approach similar to that used for the milling unit model has been used for the juice screen:

$$S_{Cn} = \frac{S_{TFCn}}{F_{TF}} \tag{30}$$

where S_{Cn} is the juice screen separation efficiency of total insoluble solids,
S_{TFCn} is the true fibre juice screen separation efficiency.

Using the model

Using fibre in juice measurements, the true fibre separation efficiency can be calculated for a milling unit. Similarly, the true fibre juice screen separation efficiency can be determined. The unknown parameter is the true fibre factor.

To determine the true fibre factor, the model should be run at different values for true fibre factor and the ratio of mud solids in mixed juice to mud solids in cane should be calculated. The required value for the true fibre factor will be the value that gives a ratio of mud solids in mixed juice to mud solids in cane equal to the ratio calculated using equation 28.

Exploring the model

The model calibration step

The model has been explored using data from a typical milling train of five milling units. This was the same milling train explored by Thaval and Kent (2012). Mill performance parameters are presented in Table 5. The model has been solved for a cane rate of 194 kg/s, with the cane containing 15.91% brix and 14% fibre. The imbibition% fibre was 200% and the true fibre content of the mixed juice was 0.2. It was assumed that the juice on fibre ratio of the return stream from the juice screen is 11.50.

Table 5. Mill performance parameters corrected for juice fibre flows.

Mill	Filling ratio (C_{On})	Reabsorption factor (K_{On})	Imbibition coefficient (I_{Con})	True fibre separation efficiency (S_{TFn}) (%)
#1	0.36	1.55	1.04	91.80
#2	0.46	1.67	0.87	91.12
#3	0.50	1.60	0.67	94.80
#4	0.55	1.59	0.57	95.41
#5	0.56	1.51	0.57	95.66

The effect of true fibre factor on the ratio of mud solids in mixed juice to the mud solids in cane was determined and is shown in Figure 4. As the true fibre factor increases, the mud solids content of the mixed juice stream increases. From the data presented by Kent (2010b) for Condong and Broadwater factories in Australia, the ratio of mud solids in mixed juice to mud solids in cane was calculated to be 0.5. Figure 4 shows that this mud solids ratio can be achieved with a true fibre factor of 1.12.

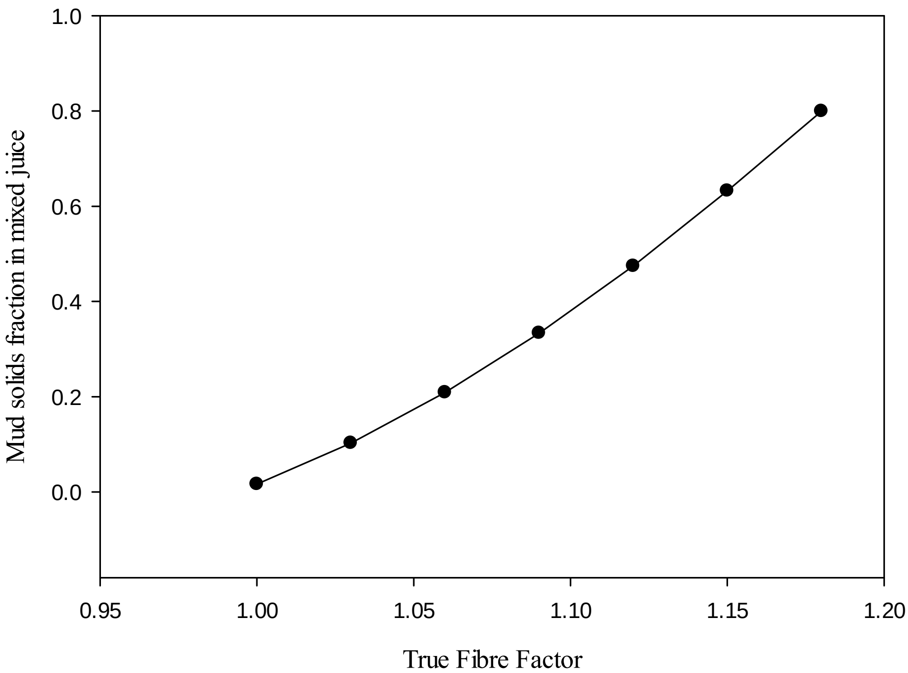


Figure 4. Effect of true fibre factor on the ratio of mud solids in mixed juice to mud solids in cane.

Results from the model

The mill extraction model provides the mass flows of brix and fibre in bagasse and juice of individual milling units along with the return stream from the juice screen and the mixed juice stream. Figure 5 shows the relative flows of brix and fibre in all the mill streams.

Using the purity ratio concept and the brix flow of the mill streams shown in Figure 5, the mass flow of pol in the milling train can be modelled. The invert ratio, ash on brix ratio and proteins on brix ratio were used to model the flow of reducing sugars, soluble ash and proteins, respectively, in the milling process. The invert ratio is determined from Table 2. The ash on brix ratio and proteins on brix ratio are determined from Table 4. Figure 6 shows the relative mass flows of pol, reducing sugars, soluble ash and proteins in the mill streams.

The insoluble solids were modelled as discussed previously. Figure 7 shows the flow of true fibre, mud solids and insoluble ash in the mill streams.

Figure 6 shows that the majority of soluble impurities end up in the mixed juice stream while Figure 7 shows that the insoluble impurities are more evenly divided between final bagasse and mixed juice. The mud solids mass flow in #1 mill and #5 mill bagasse streams are very low. In the former, about 70% of the juice entering the mill is expressed and so are the mud solids. In the case of the final mill, input mud solids flow is reduced since there are no mud solids in the imbibition. The #2, #3 and #4 mill bagasse streams have the highest of all the mill juice mud solids mass flow. The insoluble ash mass flows follow the same trend as the mud solids mass flow.

Effect of impurities on extraction

Thaval and Kent (2012) reported that brix extraction is reduced when more insoluble solids are expressed in juice streams. With this extended model, impacts of soluble and insoluble impurities on extraction can be assessed. The effect on the more important pol extraction, as well as brix extraction can be assessed.

The effect of soluble impurities on extraction is reasonably well understood since both pol and brix are common measurements. The effect of insoluble impurities (mud solids) on extraction is not well understood.

Figure 8 shows the impact of true fibre factor, which varies the amount of mud solids in the expressed juice and mixed juice streams, on brix extraction and pol extraction. Although the true fibre contents of the expressed juice and mixed juice streams remain constant as the true fibre factor varies, the brix extraction drops about 0.4 as the true fibre factor increases from 1.0 to 1.12, corresponding to a ratio of mud solids in mixed juice to the mud solids in cane of 0.5.

The pol extraction values show a similar trend to that of brix extraction with increasing true fibre factor. The reduction in pol extraction, corresponding to the true fibre factor of 1.12 is 0.35 units.

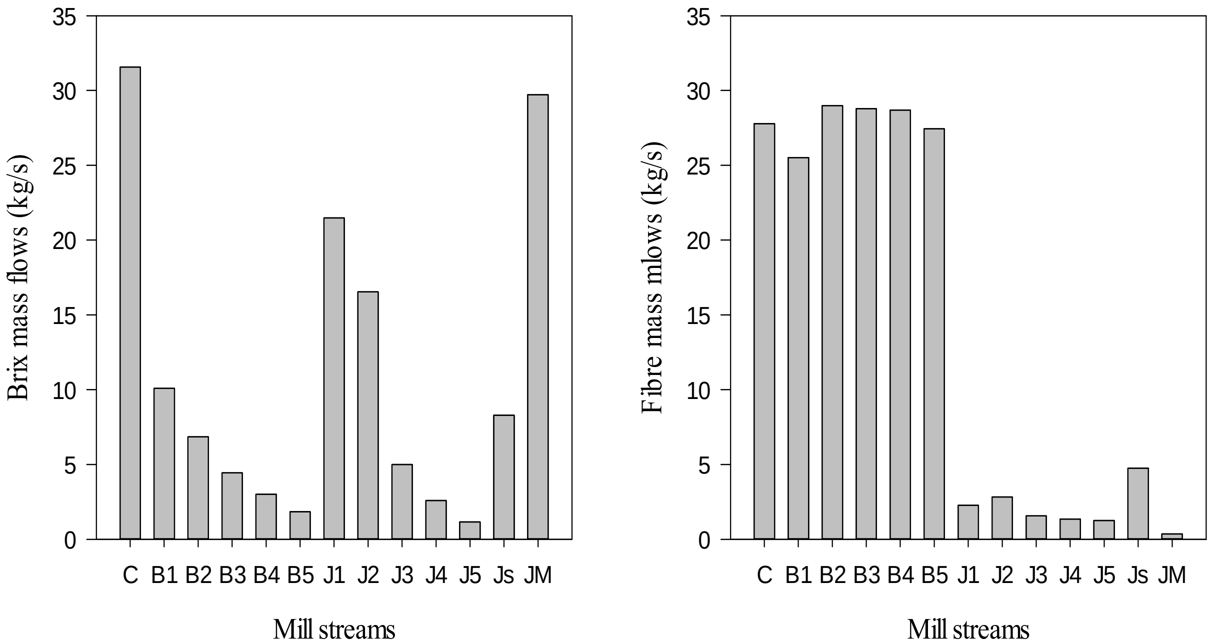


Figure 5. Mill streams brix and fibre mass flows.

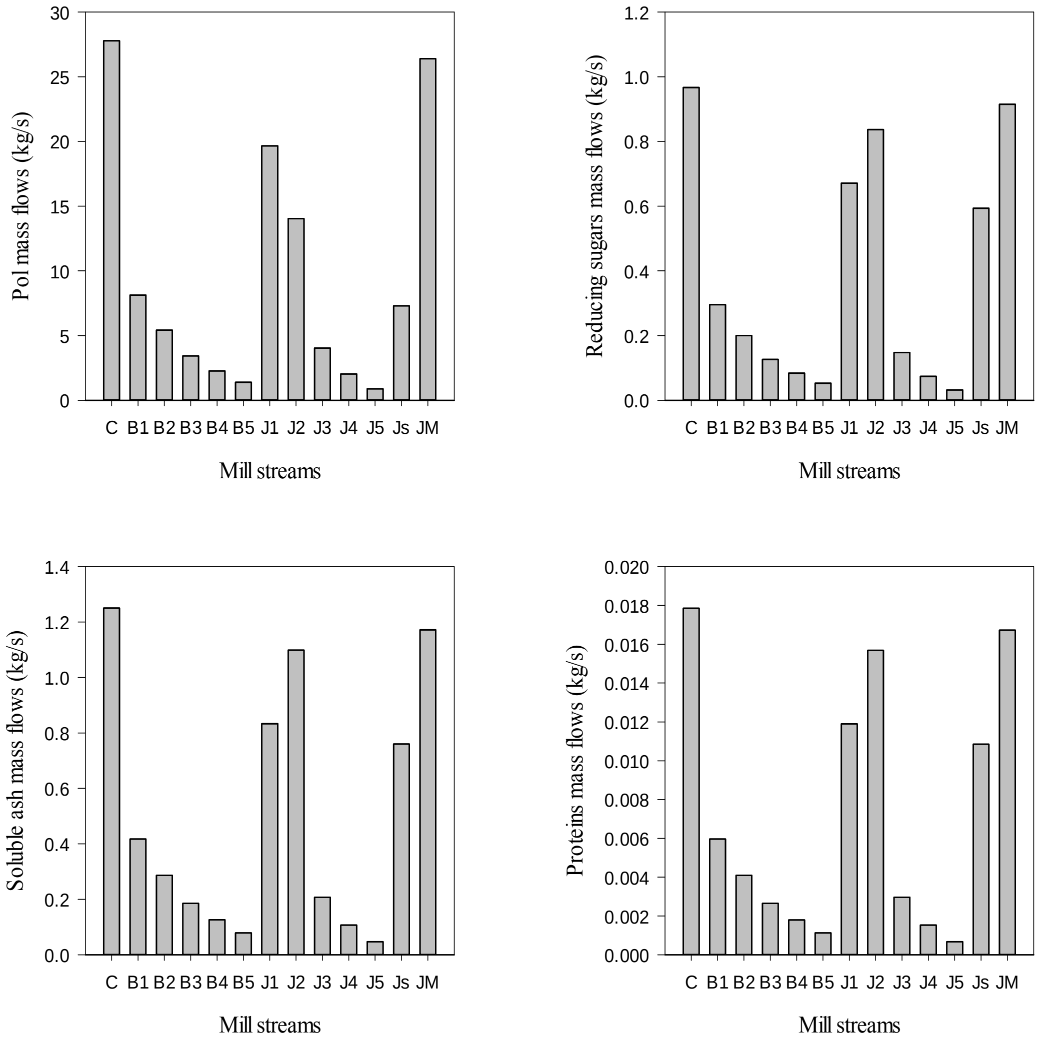


Figure 6. Mill streams soluble solids mass flows.

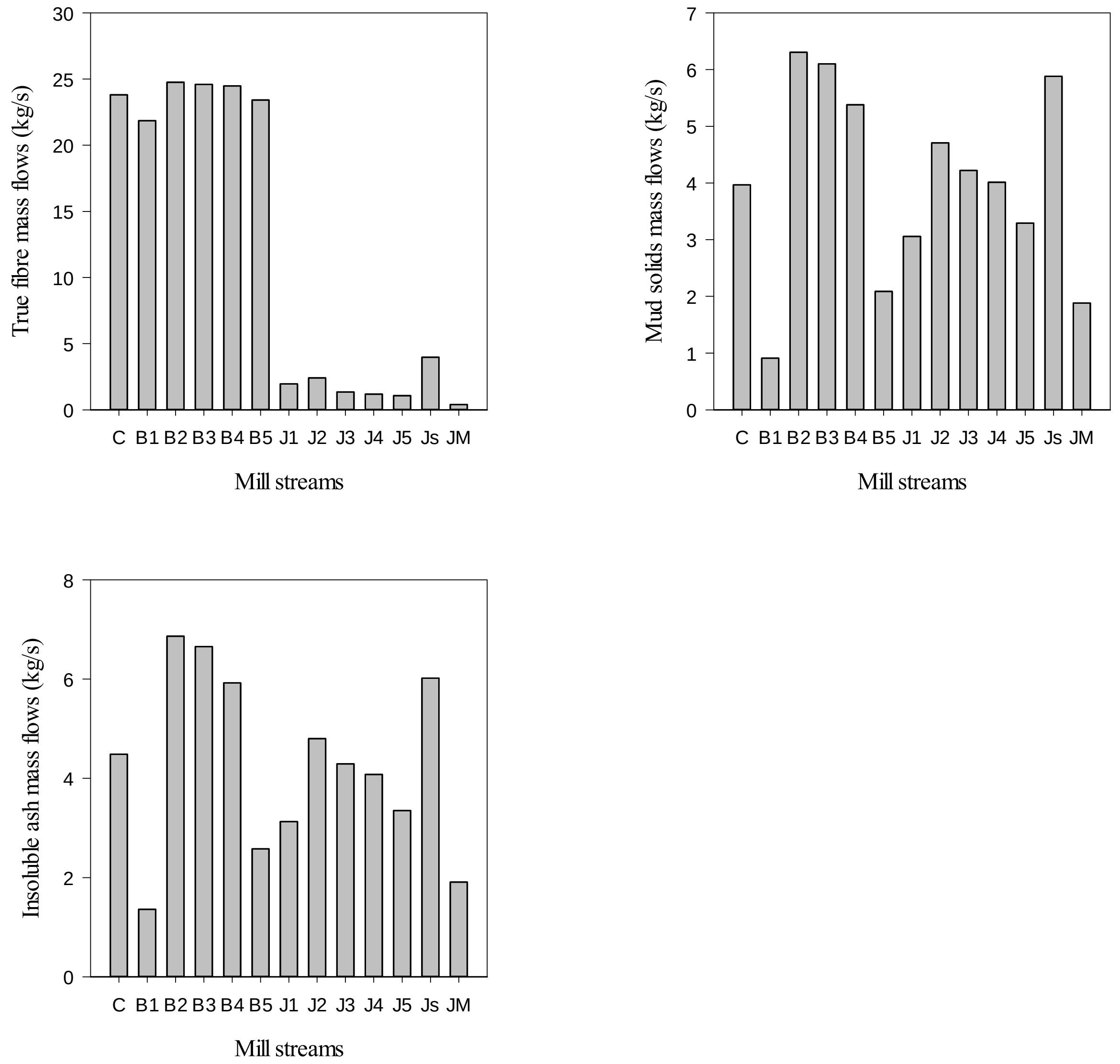


Figure 7. Mill streams insoluble solids mass flows.

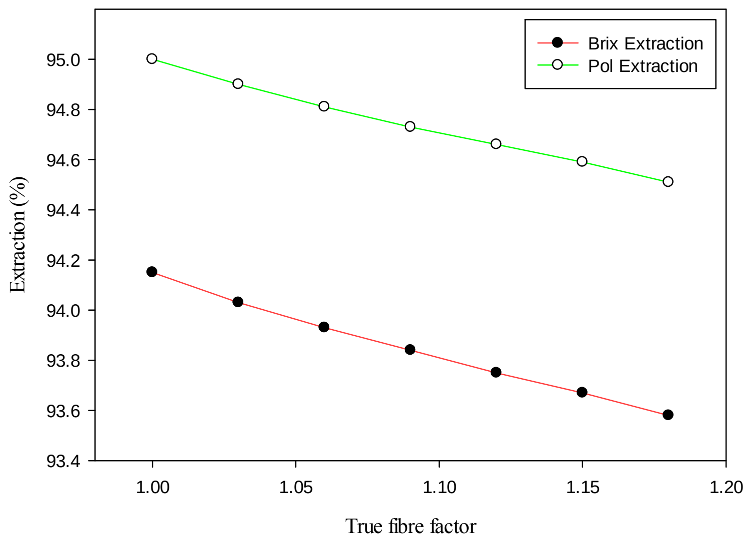


Figure 8. Effect of true fibre factor on extraction.

Conclusions

A model was developed using assumptions based on the best information available to determine the flow of cane constituents through the milling process and their distribution in juice and bagasse. The model monitors the flow of soluble and insoluble constituents. It was found that the bagasse from the #1 mill and #5 mill had less mud solids mass flow than from the other mills, while #2 mill had the highest mud solids mass flows followed by #3 and #4 mills.

The developed model can assist in understanding the effect of insoluble impurities on brix and pol extraction. Reducing the true fibre factor increases the separation efficiencies of individual milling units and reduces the insoluble solids content of juice streams. Appreciable increase in brix and pol extraction could be achieved through such actions.

The developed model is an integral part of a 'whole factory model' and tracks the flow of specific cane components in the milling train so that their concentration and mass flows are known for the downstream models.

The developed model is the first of its kind and provides some additional insight regarding the flow of soluble and insoluble cane components and the factors affecting their distribution in juice and bagasse. The model proved to be a good extension to the extraction model to study the overall performance of the milling train.

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