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An improved model of pol extraction for mills and diffusers

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Abstract Extraction models for mills and diffusers were developed to determine the brix (total dissolved solids) extraction of the process. Pol extraction was calculated from the brix extraction based on arbitrary constants or empirical relationships. The Australian sugar industry introduced a term "purity ratio" in the early 1980s and has since been using the term in extraction models to predict the pol extraction of the milling process. Here, an improved model of pol extraction is presented which replaces the purity ratio concept. The new model can be used in two different approaches, based on which brix extraction model (imbibition coefficient or crushing factor-mixing efficiency) is used. When using imbibition coefficient, an analogous term "purity coefficient" is used to determine the pol extraction of the milling unit. When using the crushing factor-mixing efficiency model for the bagasse mills, the model equations have been extended to determine the pol in delivery bagasse. The model is presented and, using factory experimental data, the results of purity coefficient of individual milling units are given. The same data is used to compare, for the bagasse mills, the measured pol and predicted pol in delivery bagasse of individual milling units.

Key words Mill extraction, diffuser extraction, brix extraction, pol extraction, purity coefficient

INTRODUCTION

Extraction models for mills and diffusers were developed to determine the brix (total dissolved solids) extraction of the process. Thaval (2012) summarises the extraction models developed to assess and predict the extraction performance of the milling process. He states that the mill engineer does not have control over the pol (sucrose) but has control over the brix and, hence, it would be reasonable to report brix extraction.

Kent (2015) states that total pol extraction, which is reported by all cane sugar factories, is the ideal parameter for quantifying the overall performance of the milling train. Therefore, it would be beneficial to be able to predict pol extraction of the process resulting from a change in operating parameters.

In modelling milling performance, pol extraction has always been calculated from the brix extraction based on arbitrary constants or empirical relationships. However, such arbitrary constants lack theoretical basis, and the empirical relationships are less reliable when simulating outside the range of the operating conditions used to develop them.

Here, we report the development of an improved model of pol extraction. The new model can be used in two different approaches, based on which brix extraction model (imbibition coefficient or crushing factor-mixing efficiency) is used. Using analysis data from a controlled factory experiment, the model was tested, and the results were compared to those of the existing purity ratio model currently used in the industry.

EXISTING POL EXTRACTION MODELS

Lionett (1981) proposed an empirical equation to determine the sucrose extraction from brix extraction based on mixed juice purity and cane purity. The data from several South African sugar factories showed that the ratio of cane purity to mixed juice purity is proportional to the sucrose extraction:

$$Sucrose\ extraction = \sqrt{1919 + 187.6 \times Brix\ extraction} - \sqrt{1919} \quad \text{Eq .1}$$

Wienese (1995) extended his 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. The equation takes the form:

$$Sucrose\ extraction = a \times Brix\ extraction^2 + b \times Brix\ extraction + c \quad \text{Eq .2}$$

where, "a", "b", "c" are constants.

To calculate these constants, three brix extraction results and their corresponding sucrose extraction results must be known. The first is 0% brix extraction corresponding to 0% sucrose extraction. The second is 100% brix extraction corresponding to 100% sucrose extraction. The third is the standard brix extraction corresponding to standard sucrose extraction determined from the data. With these three constants known, matching sucrose extraction can be calculated from the non-standard data (Thaval 2012).

The Sugar Research Institute in the early 1980s developed a model for sucrose based on the concept of a purity ratio. The purity ratio was defined as:

$$ZR_n = \frac{Z_{Bn}}{Z_C} \quad \text{Eq .3}$$

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

The purity ratio can be calculated from the cane and bagasse analysis data when running the model in analytical mode. In the predictive mode of the model, the purity in delivery bagasse of each mill is calculated from the purity ratio and cane purity.

In the earlier versions of the MILSIM (Russell 1968) model, standard values of purity ratios for each milling unit were assumed constant when running the model in the predictive mode. In the later versions of MILSIM models and the MILEX models (Thaval 2012), empirical relationships for purity ratio were developed (Thaval and Kent 2015).

However, the purity ratio concept has no theoretical basis and was adopted to determine the pol extraction of the milling process as it was convenient and gave good results (Thaval 2012).

NEW POL EXTRACTION MODEL

For the purpose of this paper, it is assumed that the pol in cane, similar to the brix in cane, is evenly distributed across the entire stalk of the cane. In reality, this assumption is not true, since the nodes have higher level of impurities than the internodes and lower internodes usually have higher levels of sucrose than upper ones.

Purity coefficient

To assess and predict the brix extraction of the milling unit, a performance indicator "imbibition coefficient" was developed (Russell, 1968). The imbibition coefficient is defined as the ratio of the actual brix extraction to the theoretical brix extraction of the mill (assuming perfect mixing of the imbibition juice and residual juice in bagasse from the previous mill) (Munro 1963, 1964).

$$I_{Cn} = \frac{E_{Bn}}{E_{kBn}}$$ Eq .4

where, I_{Cn} is the imbibition coefficient of the n^{th} mill,

E_{Bn} is the brix extraction of the n^{th} mill,

E_{kBn} is the theoretical brix extraction of the n^{th} mill.

Equivalently, in order to assess and predict the pol extraction of the milling unit, a performance indicator "purity coefficient" can be defined as the ratio of the actual pol extraction to the theoretical pol extraction.

$$ZC_n = \frac{E_{Pn}}{E_{kPn}}$$ Eq .5

where, ZC_n is the purity coefficient of the n^{th} mill,

E_{Pn} is the pol extraction of the n^{th} mill,

E_{kBn} is the theoretical pol extraction of the n^{th} mill.

The theoretical pol extraction of the milling unit is defined as:

$$E_{kPn} = \frac{X_{B(n-1)P} - X_{kBnP}}{X_{B(n-1)P}}$$ Eq .6

where, X_{BnP} is the actual pol in delivery bagasse of the n^{th} mill per unit mass of fibre

X_{BnP} is the theoretical pol in delivery bagasse of the n^{th} mill per unit mass of fibre.

The theoretical pol in delivery bagasse can be calculated from:

$$X_{kBnP} = Z_{kBn} \times X_{kBnB}$$ Eq .7

where, Z_{kBn} is the theoretical purity of delivery bagasse of the n^{th} mill

X_{kBnB} is the theoretical brix in delivery bagasse of the n^{th} mill per unit mass of fibre

The theoretical brix in delivery bagasse is determined from the equations presented by Russell (1968). The theoretical purity of delivery bagasse can be calculated from:

$$Z_{kBn} = \frac{X_{InP} + X_{B(n-1)P}}{X_{InB} + X_{B(n-1)B}}$$ Eq .8

where, X_{InP} is the pol in imbibition to the n^{th} mill per unit mass of fibre

$X_{B(n-1)P}$ is the pol in bagasse of the preceding mill per unit mass of fibre

X_{InB} is the brix in imbibition to the n^{th} mill per unit mass of fibre

$X_{B(n-1)B}$ is the brix in bagasse of the preceding mill per unit mass of fibre

In analytical mode of the extraction model, the measured pol in delivery bagasse can be used to determine the purity coefficient of each milling unit. In the predictive mode of the model, the purity coefficient is used to predict the pol in delivery bagasse and consequently the pol extraction of the milling train.

Crushing factor–Mixing efficiency (extended) model for pol

Kent (1997) proposed a model which replaces the “imbibition coefficient” indicator with two new indicators for the bagasse mills. These new indicators namely; “crushing factor” and “mixing efficiency” describe and quantify the physical process of mill extraction.

Crushing factor describes the preparation stage and is defined by:

$$G_n = \frac{B^c_{n-1} - B^c_n}{B^c_{n-1}} \qquad \text{Eq .9}$$

where, G_n is the crushing factor of the n^{th} mill,

B^c_{n-1} is the brix in closed cells per unit mass of fibre in delivery bagasse from the preceding mill

B^c_n is the brix in closed cells per unit mass of fibre in delivery bagasse of the n^{th} mill,

The brix in closed cells per unit mass of fibre in bagasse is determined by:

$$B^c_n = B_n \times PCC \qquad \text{Eq .10}$$

$$PCC = 100 - POC \qquad \text{Eq. 11}$$

where, B_n is the brix in delivery bagasse per unit mass of fibre of the n^{th} mill,

PCC is pol in closed cells (%)

POC is pol in open cells (%)

The POC measurement is routinely undertaken for cane samples to determine and assess the performance of the cane preparatory devices, but it is rarely carried out on bagasse samples. The POC value gives an indication of the percentage of cells opened during cane preparation.

Redefining Eq. 9 in terms of pol rather than brix and rearranging, the crushing factor of the n^{th} mill can be used to determine the pol in closed cells per unit mass of fibre in delivery bagasse.

$$P^c_n = (1 - G_n) \times P^c_{n-1} \qquad \text{Eq .12}$$

where, P^c_{n-1} is the pol in closed cells per unit mass of fibre in delivery bagasse from the preceding mill

P^c_n is the pol in closed cells per unit mass of fibre in delivery bagasse of the n^{th} mill,

Mixing efficiency describes the mixing stage and is defined by:

$$\eta_n = \frac{B^o_{n-1} - B^u_n}{B^o_{n-1}} \qquad \text{Eq .13}$$

where, η_n is the mixing efficiency of the n^{th} mill,

B^o_{n-1} is the brix in open cells per unit mass of fibre prior to adding imbibition in delivery bagasse from the preceding mill

B^u_n is the brix in open cells per unit mass of fibre which does not participate in mixing.

M^o_{n-1} is the moisture in open cells per unit mass of fibre prior to adding imbibition in delivery bagasse from the preceding mill

M^u_n is the moisture in open cells per unit mass of fibre which does not participate in mixing.

Similarly, mixing efficiency could also be defined as:

$$\eta_n = \frac{P^o_{n-1} - P^u_n}{P^o_{n-1}} \quad \text{Eq .14}$$

where, P^o_{n-1} is the pol in open cells per unit mass of fibre prior to adding imbibition in delivery bagasse from the preceding mill
P^u_n is the pol in open cells per unit mass of fibre which does not participate in mixing.

The mixing efficiency is calculated from the bagasse analysis based on brix and moisture measurements. Once the mixing efficiencies of individual mills are established, Eq 14 is used to determine the pol in open cells per unit mass of fibre which does not participate in mixing (P^u_n).

The bagasse exiting a mill is exposed to imbibition juice which mixes with the bagasse. This mixed bagasse is referred to as feed bagasse for the succeeding mill. The pol in feed bagasse per unit mass of fibre that participates in mixing can be calculated from:

$$P^{of}_n = P^o_{n-1} + P^i_n - P^u_n \quad \text{Eq .15}$$

where, P^i_n is the pol in open cells per unit mass of fibre in imbibition to the n^{th} mill.

The purity fraction in this feed bagasse can be calculated from:

$$Z^{of}_n = \frac{P^{of}_n}{B^{of}_n} \quad \text{Eq .16}$$

where, Z^{of}_n is the purity fraction in feed bagasse of the n^{th} mill
B^{of}_n is brix in feed bagasse per unit mass of fibre of the n^{th} mill

The pol in expressed juice per unit mass of fibre can be calculated from:

$$P^e_n = Z^{of}_n \times B^e_n \quad \text{Eq .17}$$

where, P^e_n is the pol in expressed juice per unit mass of fibre of the n^{th} mill
B^e_n is the brix in expressed juice per unit mass of fibre of the n^{th} mill

The component of pol in open cells from the feed bagasse that participated in mixing but was not expressed can be calculated from:

$$P^{or}_n = P^{of}_n - P^e_n \quad \text{Eq .18}$$

where, P^o_n is the pol in delivery bagasse per unit mass of fibre of the n^{th} mill

The pol freed from the closed cells in delivery bagasse by mill n can be calculated from:

$$P^p_n = P^c_{n-1} - P^c_n \quad \text{Eq .19}$$

where, P^c_n is the pol in delivery bagasse freed from the closed cells per unit mass of fibre of the n^{th} mill

The total pol in open cells in delivery bagasse can be calculated from:

$$P^o_n = P^{or}_n + P^u_n + P^p_n \quad \text{Eq .20}$$

where, P^{cp}_n is the pol in delivery bagasse left unopened per unit mass of fibre of the n^{th} mill

The pol in delivery bagasse can be calculated from:

$$P_n = P_n^o + P_n^c \qquad \text{Eq .21}$$

where, P_n is the pol in delivery bagasse per unit mass of fibre of the n^{th} mill

TESTING THE MODEL

Data used

The new pol extraction model was tested with the results from a controlled factory experiment conducted by SRI in the late 1990s. Sixteen tests were undertaken to determine the effect of cane preparation, mill torque, mill speed and added water (imbibition to last mill) on mill extraction performance. In addition to understanding the effect of operating conditions on mill performance, the bagasse analysis results from the experiment were used to develop empirical relationships for performance indicators for MILSIM and MILEX models (Thaval and Kent 2015).

The data was also used to determine the purity coefficient of individual mills and the extended model was used to predict the pol in delivery bagasse for the 16 tests.

Purity coefficient results

Figure 1 shows the measured imbibition coefficient and purity coefficient results for individual mills; the purity coefficient follows largely the same trend as imbibition coefficient for the same mill.

Measurements have shown that imbibition coefficient decreases along the milling train, because the difference between brix fraction of juice in the bagasse, and the brix fraction in the imbibition applied to it increases for later mills in the milling train (Thaval 2012). Similarly, purity coefficient would decrease along the milling train, since the difference between the purity of juice in the bagasse, and the purity of the imbibition applied to it increases for later mills.

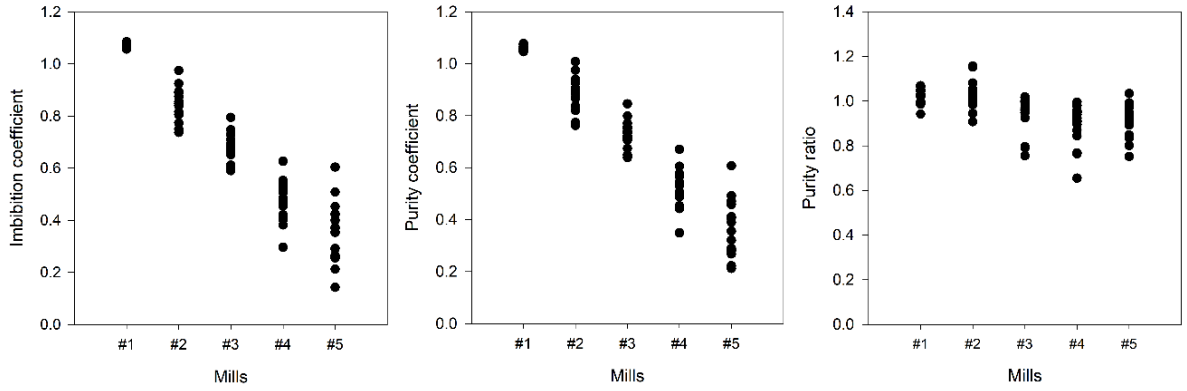

Figure 1. Measured imbibition coefficient, purity coefficient and purity ratio results for individual mills.

The imbibition coefficient and purity coefficient results for the final (#5) mill are in the range of 0.15 to 0.6 (average 0.35), indicating low brix and pol extraction at the final mill, respectively. The purity ratio value for the final mill is in the range of 0.75 to 1.03 (average 0.91). At the final mill, the bagasse has undergone four consecutive crushing operations with increasing delivery nip compactions from #1 to #4 mill. The effect of consecutive crushing operations can also be seen by the increase in the cumulative pol in open cells (CPOC, %) (Figure 2). When using the purity ratio model, even if the brix extraction of the mill is low, a higher value of purity ratio would result in predicting a higher pol extraction.

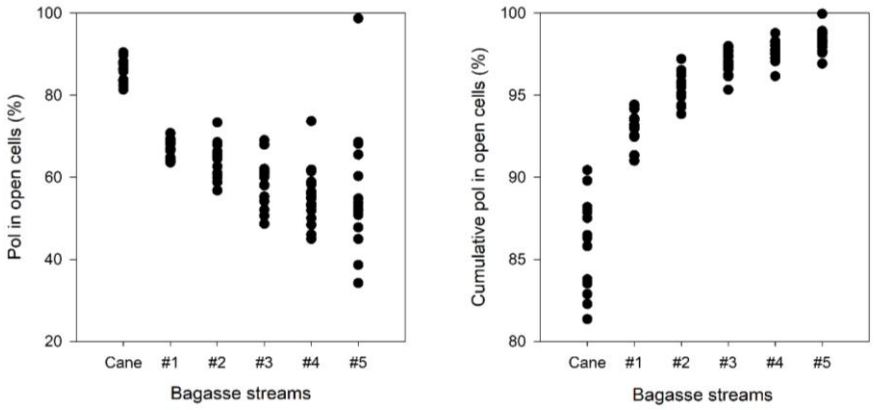

Figure 2. Measured pol in open cells (%) and cumulative pol in open cells (%) for cane and bagasse streams.

Extended model

The extended model was used to determine the pol per unit mass of fibre in delivery bagasse of individual mills. The model is only applicable for the bagasse mills (mills which have imbibition applied) and not for the first mill.

Figure 3 shows the measured and predicted pol in delivery bagasse for the #2, #3, #4 and #5 mills. In general, there is good agreement between the measured and predicted pol in delivery bagasse. The disparity between the measured and predicted pol values are also due to the errors associated in measuring brix and moisture in delivery bagasse (affecting the calculated values of crushing factor and mixing efficiency) and the errors associated in measuring pol in delivery bagasse.

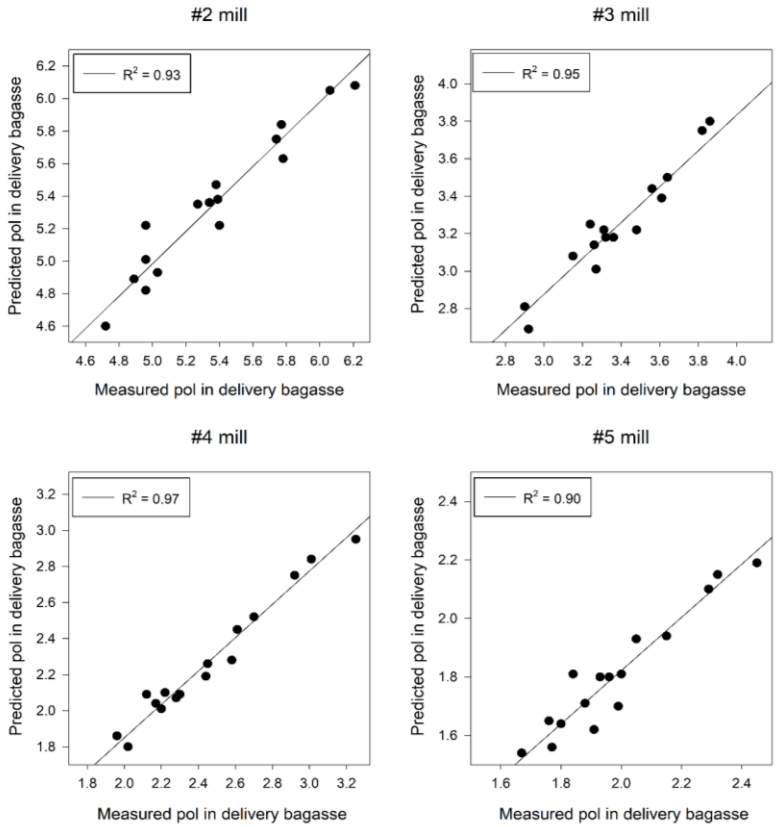

Figure 3. Measured and predicted pol in delivery bagasse for #2, #3, #4 and #5 mills using the extended model.

Model comparisons

Using the purity coefficient and extended models, the pol in delivery bagasse was predicted. Of these values, the predicted pols in delivery bagasse of the final (5^{th}) mill were compared against the same factory measurements as Thaval and Kent (2015).

When using the purity coefficient model, one of the 16 tests was chosen to determine the performance parameters from the bagasse analysis and the empirical equations in the analytical mode of the model. The calculated multipliers were then kept constant, and the model was used to predict the bagasse analysis from cane input and operating conditions for the remaining 15 tests. When using the extended model, the crushing factor and mixing efficiency values for the mills can either be calculated from the bagasse analysis or through the empirical relationships. Once the crushing factor and mixing efficiency values are established, Eq 10 to Eq 21 can be used to determine the pol in delivery bagasse.

Quality of fit was assessed from the sum of squared differences between the measured and predicted values (Table 1). Thaval & Kent (2015) presented the pol extraction predictions from five empirical models: three MILSIM versions and two MILEX versions. The final-bagasse pol predictions from these previous models were compared to the purity coefficient and the extended models.

The extended model outperforms all the previous empirical models in predicting the pol in delivery bagasse The standard deviation of the extended model is also the lowest of the models. The purity coefficient model performs to the same level as the MILEX-2 and MILEX-3 models.

Table 1. Sum of squares of Thaval and Kent (2015) final-bagasse pol measurements with predictions from seven models.

Model	Sum of squares	Standard deviation
MILSIM-1	0.65	0.21
MILSIM-2	0.66	0.21
MILSIM-3	1.24	0.20
MILEX-2	0.84	0.24
MILEX-3	0.96	0.19
Purity coefficient	0.94	0.23
Extended	0.57	0.07

Application of the extended model

The extended model could be used for predicting the pol in delivery bagasse, but it requires the crushing factor and mixing efficiency values for the bagasse mills. The lack of precision of the pol-in-open-cells (%) measurements makes the crushing factor and mixing efficiency calculations less precise than the imbibition coefficient calculations (Kent 1997). Kent (1997) assumed that the extra information to be gained from the crushing factor and mixing efficiency model will outweigh the loss in precision of the values of the performance indicators.

The lack of precision in the pol-in-open-cells measurements in bagasse samples arises from the errors associated with the sampling procedures and analytical procedures. For the later mills in the milling train, the pol quantities in bagasse are small and repeated analysis is required to improve the precision.

Another way of determining the crushing factor and mixing efficiency values is through empirical relationships. An empirical relationship defines the performance indicators in terms of operational values that are known to affect them. For example, crushing factor that determines the fraction of closed cells in the bagasse opened in a mill is understood to be largely affected by nip compaction. Hence, at high nip compaction the bagasse blanket is squeezed harder. This higher compaction should result in more cells opened in the delivery bagasse of the mill and, consequently, a higher value of crushing factor.

An empirical relationship for crushing factor is used to determine the relative percentage of pol in open cells (%) in delivery bagasse of individual mills. The inputs to the model include cane quality parameters and cane preparation level. The calculated pol in open cells (%) can be used in conjunction with the bagasse analysis to determine the mixing efficiency values for bagasse mills.

Figure 4 shows the mixing efficiency multipliers calculated from the measured POC data from the data set utilised by Thaval and Kent (2015) and the mixing efficiency multipliers calculated from the predicted POC data from the crushing factor empirical relationship.

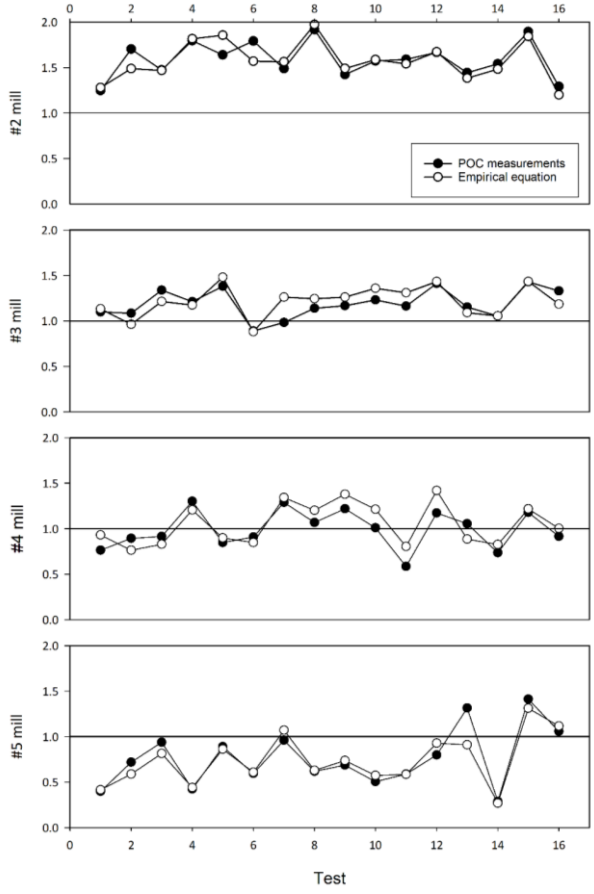

Figure 4. Mixing efficiency multipliers based on POC measurements and crushing factor empirical relationship.

The two factors affecting the predicted values of pol in open cells (%) in delivery bagasse of individual mills are cane preparation and mill torque. Since the empirical relationship for crushing factor includes the delivery nip compaction parameter, the effect of a change in delivery nip compaction on the predicted values of pol in open cells (%) in delivery bagasse of individual mills cannot be assessed. However, the effect of a change in cane preparation can be assessed.

Pol extraction model for diffusers

Thaval (2023) proposed a model that defines the extraction process of the diffuser in three phases. New non-dimensional performance indicators were developed, namely mixing factor, percolation factor and diffusion factor. The mixing factor and diffusion factor of the diffuser extraction model are analogous to the mixing efficiency and crushing factor of the mill extraction model. The diffuser model was developed for brix extraction only.

The extended model for pol extraction introduced here is also applicable to the diffuser model. Using Eq 9 to eq 21 and replacing the mixing efficiency and crushing factor with mixing factor and diffusion factor, the pol extraction of the diffusion process can be determined. To account for the press water (expressed juice from the de-watering mill), the purity coefficient model for the de-watering mill can be used. Similarly, if the diffuser station contains a #1 milling unit (bagasse diffuser), the pol extraction of the mill can be calculated from the purity coefficient.

CONCLUSIONS

We developed an improved model of pol extraction that replaces the purity ratio concept used in the Australian sugar industry's brix-based extraction models to determine the pol in delivery bagasse and the pol extraction of the milling train. There are two versions of the new model, based on the imbibition coefficient and crushing factor-mixing efficiency brix extraction models. For the imbibition coefficient approach, an analogous term "purity coefficient" is used to determine the pol extraction of the milling unit. For the crushing factor-mixing efficiency approach for the bagasse mills, the crushing factor and mixing efficiency equations have been extended to determine the pol in delivery bagasse.

The purity coefficient is the ratio of the actual pol extraction to the theoretical pol extraction. An empirical relationship for purity coefficient was developed and is a function of pol in bagasse entering the mill, pol in imbibition to the mill, and filling ratio of the mill. The extended model uses the crushing factor and mixing efficiency of the mill to determine the total pol in delivery bagasse per unit mass of fibre. If POC measurements of the individual mill bagasse streams are not available, the crushing factor empirical relationship can be used to determine the mixing efficiency values and subsequently the pol in delivery bagasse.

The new model was tested with factory measurements from a controlled milling experiment. The results from the model highlighted the deficiencies of the purity ratio concept. When comparing the new pol extraction model with the previous empirical models, it was evident that the extended model for pol extraction (crushing factor-mixing efficiency) outperformed all the previous pol extraction models.

The extended model for pol extraction can also be applied to the diffuser extraction model.

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