CONTINUOUS PERCOLATION RATE MEASUREMENT IN A SUGARCANE DIFFUSER

JENSEN PS

Sugar Milling Research Institute NPC, University of KwaZulu-Natal, Durban, 4041, South Africa
pjensen@smri.org

Abstract

Percolation rate in a sugarcane diffuser is the volumetric flow rate of juice through a unit area of the cane bed. Maximising the percolation rate is important for maximising the sucrose extraction from the cane. For each consignment of cane in the diffuser, a maximum percolation rate (MPR) exists. Increasing the rate of juice applied to the cane to above the MPR results in flooding, with well-known negative consequences. Applying juice to the cane at well below the MPR results in lower extraction levels than could otherwise be obtained. There is currently no means of continuously measuring percolation rate in any of the diffusers installed in South African sugar factories. Spot checks, for example tracer tests, are periodically performed, but these are usually labour intensive and do not account for fluctuations in percolation rate with cane throughput, imbibition flow rate, or different cane varieties. A magnetic flowmeter was installed on one of the interstage flow lines on the BMA diffuser installed at the Maidstone factory (the ‘Tongaat’ diffuser). The flowmeter provided real time data of the percolation rate of juice through the cane above the tray from which the flow was measured. The results showed that the percolation rate was well below the expected MPR of the cane, and this explained the ‘dry’ bed which was observed through the diffuser sight glass. A wide range of interstage flow rates were observed and fibre blockages in the line were the most likely cause. Suggestions were given for how to use the continuous percolation rate measurement method to automatically control diffuser spray flap positions.

Keywords: diffusion, percolation rate, extraction

Introduction

Percolation rate in a sugarcane diffuser is the volumetric flow rate of juice through a unit area of the cane bed. Different cane varieties and levels of extraneous matter (e.g. sand) result in the maximum percolation rate (MPR) of the bed fluctuating with time. Other major factors affecting the MPR are level of preparation, the fibre packing density within the cane bed and the extent to which particles move within the bed and cause plugging. If processing conditions remain constant these other factors can all be expected to be primarily dependent on cane quality. In order to avoid flooding, the diffuser is normally set up so that the interstage flow rates correspond with the MPR of the worst percolating cane that the mill normally receives. Ideally, the interstage juice application positions should be changed continuously to account for these fluctuations, but there are currently no South African diffusers using automatic spray position control. Instead, operator experience and vigilance is relied upon, and the decreasing extraction trend in the South African industry suggests that these skills are in decline. A number of spot trials have been performed in the past to assess
diffuser percolation rates. These, however, do not say much about the fluctuation of the percolation rate with time, or necessarily whether the MPR is being approached in the diffuser. A spot test also offers little feedback on the effect that changing a variable (e.g. spray position or degree of preparation) has on the percolation rate. A method for continuously monitoring percolation rate would be valuable for understanding the juice flow patterns in a diffuser, and could be used to automatically control the positioning of sprays to optimise performance under a wide range of operating conditions.

**Literature survey and methods of percolation rate measurement**

Rein (2007) suggested that percolation rate of juice through the cane mat is the second most important variable affecting extraction in a diffuser (after cane preparation). High liquid flow rates promote extraction by increasing the rate of mass transfer and by improved wetting of cane particles (Rein and Ingham, 1992). Percolation velocity (m/min) is the downward velocity of the liquid as it moves between cane particles. Percolation rate (m³/m²/min) is the volumetric flow rate of juice through a unit area of the cane bed (i.e. the superficial velocity of liquid through the bed). The ratio of percolation velocity to percolation rate is generally around 0.7, and this reflects the voidage, or area open for flow, between the fibres (Love and Rein, 1980).

Given the importance of maximising percolation rate, it is not surprising that a variety of measurement techniques have been attempted. These include:

1. **Interface velocity test:**
   
   All interstage pumps are stopped simultaneously and the rate of descent of the juice/air interface in the cane is observed through the sight glass in the diffuser wall. This linear velocity (m/min) may then be converted to a percolation rate (m³/m²/min) through multiplication by a numerical factor of 0.7, which accounts for bed voidage.

   A disadvantage of this method is that the sample of juice and cane viewable through the sight glass is very small compared to the size of the stage being examined. Variations in bed height across the width of the diffuser may result in zones of higher and lower percolation. The position of the sight glass relative to the juice spray position will also contribute to the inaccuracies of this method. Furthermore, laboratory observations by the author (Figure 1) show that, even under conditions where the interface level is both clearly visible and representative of the level in the entire sample being viewed, percolation rate estimated by this method does not accurately predict the percolation rate calculated by measuring the flow rate of juice exiting the column. The dotted line in Figure 1 represents a perfect prediction. It can be seen from the position of the solid trendline that the interface velocity method tends to over-predict the percolation rate in the column. An R² value of 0.81 shows that some correlation exists, although it is expected that on a full scale diffuser this correlation would be of little value.
2. Dynamic tracer tests (Matthesius, 1977):
A sodium chloride tracer is added to the juice at the suction side of an interstage juice pump. The conductivity of the juice exiting the trays below the spray is monitored, and the percolation velocity is determined by the average time taken for the tracer to exit the bed. This value is multiplied by 0.7 for conversion into a percolation rate.

Tracer tests performed in this way are labour intensive – particularly when it comes to interpreting the results of the tests. The percolation rate in all the trays where the juice conductivity is being measured (usually 3-5 stages) is assumed to be the same, which is probably not the case. Furthermore, due to the variation of cane being delivered to the factory, consecutive tracer tests performed on the same day may give very different results. Another disadvantage of the tracer test method is that it can never be used to measure the MPR of the cane bed, as any juice on top of the bed would accelerate the dispersion of the tracer lengthways along the diffuser.

3. Static tracer tests (Matthesius, 1977):
The static tracer test differs from the dynamic test in that the movement of the diffuser bed is stopped during this test. Only the conductivity in the tray beneath the spray needs to be monitored, which makes this test simpler to perform than the dynamic test.

The other concerns of the dynamic tracer test method described above would still apply to this method.

By installing juice samplers (Figure 2) of known open area beneath the screen, and measuring the flow rate of juice from each sampler, the percolation rate of juice through the cane bed can be estimated.
This method is useful for understanding the percolation profile across a stage. It is expected that larger samplers than were used by Matthesius (one inch pipes cut in half) would be required to estimate the actual percolation rate, due to the splashing of juice from each sampler. Matthesius showed a wide range of percolation rates detected by each sampler, which indicates that a number of samplers would be required in order to obtain a representative percolation rate for an entire stage. The method is also labor intensive, with a bucket and stopwatch being required to measure the flow rate from each sampler.

5. Juice level method:
Although not a direct measurement of percolation rate, if the juice level in the bed could be measured, it would give feedback as to how closely the percolation rate in the diffuser is approaching the MPR (where the juice level equals the cane bed height). Rein and Ingham (1992) published data recorded from pressure transmitters mounted to the side of a diffuser which attempted to continuously monitor the hydrostatic pressure in the cane bed. Furthermore, the readings from these transmitters may be used to control the juice spray positions with the aim of controlling the level of juice in the cane bed.

Typical percolation rates in laboratory and factory diffusers
Measurements of percolation rates in full-scale diffusers have been found to cover a range from 0.1 to 0.2 m³/m²/min (Rein, 2007). These values may not reflect the MPR of the cane as factory measurements are usually undertaken when the diffuser is not flooding. Percolation rates in laboratory columns are generally between 0.3 and 1.0 m³/m²/min and are largely dependent on the fibre packing density (Lionnet, 2005). Laboratory percolation rate tests are usually performed under slightly flooded conditions, which may be a reason why they are higher than factory rates.

Column percolation tests carried out at the Sugar Milling Research Institute (SMRI) in a glass column by Barker¹ show that the MPR tends to decrease exponentially with time as the cane compacts (Figure 3). Diffusers are typically 60 m long, and the chain speed usually between 0.6 and 1.2 m/min, leading to a cane residence time of ~60 minutes.

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¹Personal communication, Mr B Barker, Sugar Milling Research Institute, South Africa (2013).
Figure 3. Maximum percolation rate (MPR) decrease with time in a glass column.

Variation of percolation rate along the length of a diffuser

It may seem logical to assume that a percolation profile along a sugarcane diffuser would take a similar shape as the curve in Figure 3, and while this is generally the case due to the rate of compaction of the cane, this assumption is complicated by at least two other factors:

(i) Variation in MPR between adjacent consignments of cane

A 200 tch diffuser contains ~200 t of cane during normal operation. Based on a 25 t payload, this equates to ~8 loads of cane in the diffuser at any given time. These could be different varieties, of different maturity, from different growers, with different amounts of extraneous matter (e.g. sand). Table 1 shows the order of arrival of different varieties of cane at Maidstone factory over a randomly selected time period.

Table 1. Sample of cane delivery results (where Unk refers to unknown varieties) to Maidstone factory on 19/11/2012.

<table>
<thead>
<tr>
<th>Variety</th>
<th>N39</th>
<th>N37</th>
<th>Mix</th>
<th>N39</th>
<th>N42</th>
<th>Unk</th>
<th>N39</th>
<th>NCo376</th>
<th>N39</th>
<th>Unk</th>
<th>Unk</th>
<th>N31</th>
<th>N29</th>
<th>N31</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (t)</td>
<td>32</td>
<td>32</td>
<td>14</td>
<td>34</td>
<td>32</td>
<td>31</td>
<td>27</td>
<td>15</td>
<td>34</td>
<td>33</td>
<td>31</td>
<td>24</td>
<td>29</td>
<td>33</td>
</tr>
</tbody>
</table>

Loubser and Barker (2011) showed the difference in MPR between varieties to be significant, as illustrated in Figure 4. All the trials were performed on clean cane. Unfortunately, none of the varieties from Table 1 are reflected in Figure 4, although a similar range of percolation rates could be expected. Based on the above observation, and looking at random orders of delivery of the various varieties of cane to the factory, it is evident that the MPR profile along the diffuser can vary greatly, depending on the combination (comb) of cane varieties (Figure 5).

In order to avoid flooding in certain sections of the diffuser, the sprays would normally be set up so that the percolation rate in the diffuser is close to that of the MPR of the worst percolating cane. This implies that the cane is not fully wetted in most parts of the diffuser.
Figure 4. Percolation characteristics of different cane varieties (Loubser and Barker, 2011).

Figure 5. MPR profile along a diffuser with different cane variety combinations regularly delivered to a factory.

(ii) The variation in percolation rate due to discrete spray positions

Matthesius (1977) installed a number of juice samplers under the diffuser screen as shown in Figure 6, where FES refers to the front-end stage in the diffuser. The actual flow from each sampler was divided by the open area of each sampler, and the units converted to m$^3$/m$^2$/min. The flow rate of juice collected from each sampler indicates that the percolation rate in the cane bed follows a cyclical pattern which repeats itself at each stage. The low flow rates suggest that much of the juice splashed out of the samplers, and the results are only valuable for comparing relative flow rate differences across the stage.

Figure 6. Location of samplers under the diffuser screen, and the flow rates measured at each location for Union Co-op (UCL) and Tongaat (Tg) diffusers (Matthesius, 1977).

This insight shows that the bed is not uniformly wetted, and that the percolation rate varies greatly due to the fact the sprays are in discrete positions. It is expected that this effect is less pronounced where the juice is sprayed onto the cane over a wider area as opposed to poured onto the cane in a ‘curtain’. At the time of these tests the Tongaat diffuser (BMA type) used weirs that added the juice to the top of the bed as a curtain rather than sprays that distributed the juice more widely over the surface of the bed.
It is also expected that under flooded conditions, the variation within the bed due to discrete spray positions would be negligible, and the variation of percolation rate along the diffuser would be primarily as a result of the different MPRs of the different cane consignments.

**Description of a method for the continuous measurement of percolation rate in a full scale diffuser**

In 2012, the SMRI planned to conduct Direct Clear Juice (DCJ) tests (Jensen, 2012) at Maidstone factory. One of the concerns with the technology was its possible impact on percolation rate in the diffuser. It was decided that due to the limitations of the five methods described above, continuous measurement of percolation rate would give the most reliable information on the effect of DCJ configuration on percolation rate in the diffuser.

The trial of continuous interstage juice flow measurement was performed on Maidstone’s Tg diffuser, a 220 tch BMA diffuser, which was installed in 1977. The Tongaat interstage pumps operate at a speed of 523 rpm, and have an impeller diameter of 430 mm. Diffuser interstage pumps are designed to run on ‘snore’ meaning that they run continuously to keep the juice trays empty, and can handle two phase flow of air and liquid at the suction of the pump when the tray becomes empty.

The diffuser is 6.4 m wide, with a stage length of 2.75 m, equating to a screen area of 17.6 m² per stage. An interstage flow rate of 100 m³/h thus equates to a percolation rate of ~0.1 m³/m²/min.

It was decided to measure the percolation rate at stage 9 (of 20) as indicated in Figure 7. By this stage, the cane would have been in the diffuser for ~30 minutes. A six-inch magnetic flowmeter (‘magflo’) was installed on the discharge side of the interstage pump to measure the juice flow rate. The line size was eight-inch, but a smaller magflo was chosen in order to reduce the cost of the trial. Clamp-on ultrasonic transmitters from three different manufacturers were tested, and none of them gave even remotely realistic or stable readings. It is expected that ‘scale’, found on the internal walls of most sugar factory process pipes, disrupts the ultrasonic signal. All three suppliers were nevertheless most surprised that their meters did not work.

![Figure 7. Illustration of the location of stage 9 in the Tongaat diffuser.](image)
Due to the suspected presence of intermittent two-phase flow in the line, there was also doubt that the magflo would give a stable reading. For this reason it was decided to control the juice level in tray 9. The level was measured using a bubbler tube and pressure transmitter (PT) as illustrated in Figure 8. It is important to note that even if the transmitter recorded a level of zero, the juice level in the suction line to the pump could still be anywhere between 0 and 2.2 m above the pump suction. The measurements around the stage are shown in Appendix A. A variable speed drive (VFD) was purchased to control the juice level by changing the speed of the pump. A portable PLC logged the flow and level data which enabled the trial to be monitored without disrupting normal factory operations.

![Figure 8. Instrumentation installed around stage 9 to measure the percolation rate.](image)

If the tank level remained constant, then the flowmeter (FX) would give the flow rate (m$^3$/h) of juice into tray 9 in the diffuser, which could easily be converted into a percolation rate (m$^3$/m$^2$/min). During commissioning, it was found that the level control loop was in fact unnecessary as the tank level was self-regulating to a large degree. This phenomenon will be explained in more detail in a later section of this paper.

**Results of the factory trial**

Figures 9 and 10 show the flow and level data recorded for two consecutive days during the trial. Based on the manufacturer’s data, the pump should have been able to pump at 180 m$^3$/h, but Figure 9 shows that for a number of hours, the flow rate never exceeded 116 m$^3$/h, which was not enough to drain the tank (a tank level of 80% in Figure 9 represents a full tank). It is expected that the juice would have overflowed into the adjacent cells during this period.

Flow rates of 160 m$^3$/h were seen at other times during the trial, so clearly the flow rate of 116 m$^3$/hr in Figure 9 was not the maximum capacity of the pump and fibre build-up in the tray may have caused a restriction in the pump suction. A very stable flow rate was logged due to a constant level in the tank.

Figure 10 shows the flow and level data recorded when the tank was ‘empty’. The average flow rate was 80 m$^3$/h and fluctuated between 60 and 110 m$^3$/h. The fluctuating flow rate was due to the fluctuating level in the tank which occurs under normal operating conditions.
The calculation of the theoretical interstage flow rate without any recycle or bypassing ($F_0$), based on the throughput and imbibition rate, is detailed in Appendix C, and the results are shown in Table 2. It is evident from Figures 9 and 10 that the average flow rate is below $F_0$, which shows that bypassing is occurring in the diffuser. The data shown in Figure 9, where the tray is full, suggests that bypassing is most likely occurring by the juice overflowing tray 9 into tray 8 (see Figure 7). Diffuser trays are usually aligned to ensure the juice in a filling tray will first overflow towards the ‘cane end’ of the diffuser. This ensures that, should a pump stop, the overflowing juice will bypass into the following stage rather than recycle into the previous stage. In Figure 10, however, the low juice level shown suggests that bypassing in this instance was caused by the juice percolating quickly through the cane bed. Of more concern, however, is how much lower the flows were than the flow ($F_{MPR}$) equivalent to a typical MPR (0.15 m$^3$/m$^2$/min) for the cane. This would explain the dry bed observed above stage 9 for the duration of the trial.

The calculations for the recirculation rate required for optimum diffuser operation ($R_{required}$), and the actual recycle ratio ($R_{actual}$) are shown in Appendix C.

Table 2. Actual, theoretical, and maximum percolation rate flows calculated for the data logged on 12/12/2012 and 13/12/2012 on Tongaat diffuser.

<table>
<thead>
<tr>
<th></th>
<th>12/12/2012 (16:00-20:00)</th>
<th>13/12/2012 (02:00-06:00)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cane throughput (t/h)</td>
<td>143</td>
<td>122</td>
</tr>
<tr>
<td>Imb%Fibre</td>
<td>230</td>
<td>150</td>
</tr>
<tr>
<td>$F_{actual}$ (m$^3$/h)</td>
<td>116</td>
<td>80</td>
</tr>
<tr>
<td>$F_0$ (m$^3$/h)</td>
<td>124</td>
<td>90</td>
</tr>
<tr>
<td>$F_{MPR}$ (m$^3$/h)</td>
<td>158</td>
<td>158</td>
</tr>
<tr>
<td>$R_{required}$</td>
<td>22%</td>
<td>43%</td>
</tr>
<tr>
<td>$R_{actual}$</td>
<td>-7%</td>
<td>-13%</td>
</tr>
</tbody>
</table>

Diffuser operation is optimised when $F_{actual} = F_{MPR}$ which is equivalent to saying that $R_{actual} = R_{required}$. In diffusers with variable throw sprays (Rein and Ingham, 1992), the sprays should be adjusted to increase the amount of juice being recycled until the onset of flooding, at which point $F_{actual} = F_{MPR}$. The Tongaat diffuser is rated for 220 tch, and at low throughputs combined with low imbibition rates (Imb%Fibre of 150% compared to 350% which is
commonly used), it seems the juice spray position required adjustment beyond the range capable by adjusting the flaps (Figure 11). Alternatively, the diffuser may have become ‘frozen’ in a dry position which is explained in the following section.

![Figure 11. Tongaat diffuser spray flap position adjustment.](image)

‘Unfreezing’ a dry diffuser

An interesting phenomenon was observed upon commissioning the variable speed drive on the pump. The results are shown in Figure 12, where the chart has been divided into four sections to assist the interpretation.

![Figure 12. Chart showing how the interstage flow rate may be increased after allowing the juice level in the tank to build up.](image)

A: Drive output = 91%
All juice entering the tank is being pumped away and the flow rate is 104 m$^3$/h.

B: Drive output = 75%
The flow rate dropped to 50 m$^3$/h, and the level in the tank built up until it was full (~80%).
C: Drive output = 85%
The flow rate increased to 150 m$^3$/h as a result of the increase in suction pressure to the pump. Interestingly, however, even at this flow rate, the tank level did not drop.

D: Drive output = 95%
The drive was ramped up to 95% in an attempt to drain the tank. Although the tank drained, it was observed that the average flow rate after the exercise of filling and emptying the tank was 146 m$^3$/h, where it had been only 104 m$^3$/h previously (section A).

It is expected that for diffusers running well below capacity and with low imbibition rates, even though the flaps are adjusted for maximum recycling, much of the juice tends to bypass the stage for which it was intended, thereby decreasing the interstage flow rates, and resulting ultimately in a ‘dry’ bed. One way of ‘unfreezing’ this situation is to stop all pumps briefly, and allow the level in the tanks to build up. Upon restarting the pumps, interstage flows would be at a maximum. The system is able to ‘perpetuate itself’ with more juice being recycled as more juice is pumped onto the surface of the cane.

Two-phase flow – fact or fiction?

Upon analysing the results it was evident that even without level control, the flowmeter gave a stable reading, suggesting that air was never drawn into the inlet of the pump even when the tank was ‘empty’.

To explain these observations, the system pressure drop was calculated by the ‘two-k’ method (Hooper, 1981) shown in Appendix A and Appendix B. The system pressure curve versus flow rate is plotted in Figures 13 and 14, along with the pump curves. Two possible scenarios which might explain the tray never emptying are:

1. Reduction in pump performance
   Figure 13 shows the manufacturer’s pump curve plotted on the same chart as the system curves for both a full tray and an empty tray. If the pump was operating to specification, then the flow rate should fluctuate between 145 m$^3$/h (point C) and 180 m$^3$/h (point D, which is the maximum flow rate of the pump) corresponding to an empty tray and suction line or alternatively a full tray and suction line. Under these conditions it is expected that the tray and suction lines would occasionally become completely emptied; for example, when low imbibition rates are used. It was observed during the trial that the flow rate was usually much lower than could be expected according to the above analysis based on the manufacturer’s pump curve. A possible explanation is that, due to the age of the pump (more than 30 years old) and possible wear or damage to the impeller, the pump performance is substantially lower than its original design. The pump curve was moved downwards on the graph until it intersected the lower system curve at point B, as shown in Figure 13. In this situation the flow rate would be expected to vary between 20 m$^3$/h (point A) and 170 m$^3$/h (point B), depending on the level of juice in the tray and suction line. This situation would regulate the flow to always maintain a level in the tray or suction line. The actual flow rates observed lie well within these two boundaries (never being as high or low), and so it is expected that this analysis doesn’t completely explain the system. Alternatively, the actual shape of the pump curve may be different to that obtained from the manufacturer’s literature.
2. Flow restrictions in the juice pipes caused by fibre build-up

Figure 15 shows how the geometry of the tray and juice offtake can lead to fibre blockages in the pump suction line. Although not located, damage to the diffuser screen was suspected, due to the abnormal amounts of fibre being cleaned from the juice trays on cleaning days. On one occasion, it was necessary to open the pump in order to remove a large amount of fibre which had become lodged inside it. If the flow in the juice line was restricted, then the system pressure curves shown in Figure 13 would not correctly represent the system. Another set of curves were calculated (Appendix B) for the system containing an additional restriction to account for the possibility of fibre build-up in the line. Figure 14 shows how for this situation the flow could fluctuate between 70 m$^3$/h and 120 m$^3$/h, (points E and F) which more closely represented the actual range of flow rates observed.

In hindsight, the installation of pressure measuring devices on the suction and discharge sides of the pump, would have allowed the calculation of both the actual pressure drop in the suction line, as well as the actual pump curve for the pump.

In summary, it appears that either pump inefficiency, or a restriction in the juice line contributed to lower than expected flow rates. However, due to the self-regulating nature of the system, it is doubtful whether the trays will ever run completely empty.
Discussion

The cost of the six-inch magnetic flowmeter used in the trial was R15 900. The trial was run for just a few days of operation before the end of the 2012 season. However, the insights gained into the functioning of the diffuser in this short time and without much expenditure, have been most valuable. It is expected that if installed permanently, and in particular if more than one magflo was to be installed, it would be a big help for operators and engineers in their quest to improve extraction in a diffuser at the same time as decreasing imbibition rates.

Rein and Ingham (1992) expressed the advantages of automatically controlling the juice level in a diffuser. Unfortunately, reliably measuring the juice level in the cane bed is a challenge. By measuring the interstage flow rates, however, an indirect assessment of the juice holdup in the diffuser may be obtained. This statement assumes that percolation in the diffuser is constant, which is not the case. Nevertheless, using the flowmeter, and adjusting the sprays manually until the onset of flooding, the MPR ranges of the cane being processed in the diffuser could be measured. The adjustable sprays could then be used to automatically control $F_{\text{actual}}$ to as close to $F_{\text{MPR}}$ as possible. Ideally, there should be a flowmeter on each stage, but it would be more cost effective to have, for example, one flowmeter at every third stage, controlling the flap positions of three sprays simultaneously.

Measuring the interstage flow would also be useful for diffusers that do not have adjustable sprays. Imbibition rates could then be adjusted to try to equate $F_{\text{actual}}$ to $F_{\text{MPR}}$. It was observed on the Tongaat diffuser that the imbibition rate could have been increased significantly, but evaporator constraints prevented this. For this situation it may have been beneficial to shred the cane more finely, to decrease its permeability, which would then have facilitated a ‘wetter’ cane bed.

Conclusions

- A number of methods for measuring percolation rate in a diffuser were described, each with its limitations.
- An inexpensive method for continuously monitoring percolation rate in one stage of a diffuser was described.
- The method helped to assess the performance of the diffuser, and indicated variable flow rates which were most likely the result of fibre blockages in the line.
- It is expected that the interstage flow rate measurement could be further developed and used to automatically control diffuser spray positions.

Acknowledgements

The author is grateful for the help received in preparing this paper, and would like to acknowledge inputs from Dr David Love for his advice with interpreting the results of the trial; Maidstone instrumentation department for installing and configuring the instruments and PLC; the SMRI research department for a number of insightful, informal discussions around the subject matter.
### Abbreviations used

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>MPR</td>
<td>Maximum percolation rate achievable through a sample of shredded cane</td>
</tr>
<tr>
<td>tch</td>
<td>Tonnes of cane per hour</td>
</tr>
<tr>
<td>t</td>
<td>tonnes</td>
</tr>
<tr>
<td>Tg</td>
<td>Tongaat (as in the ‘Tongaat’ BMA diffuser at Maidstone factory)</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable logic controller</td>
</tr>
<tr>
<td>PT</td>
<td>Pressure transmitter</td>
</tr>
<tr>
<td>FT</td>
<td>Flow transmitter (magnetic flowmeter)</td>
</tr>
<tr>
<td>VFD</td>
<td>Variable frequency drive</td>
</tr>
<tr>
<td>LC</td>
<td>Level controller</td>
</tr>
<tr>
<td>( F_0 )</td>
<td>Theoretical stage flow rate under zero-recycle, zero-bypass conditions</td>
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<td>( F_{\text{MPR}} )</td>
<td>Maximum interstage flow rate based on the MPR of the cane</td>
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<td>( F_{\text{actual}} )</td>
<td>Actual stage flow rate measured by a flowmeter on the interstage pipe</td>
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<tr>
<td>( R_{\text{required}} )</td>
<td>Recycle ratio required to maximise percolation (negative indicates bypassing)</td>
</tr>
<tr>
<td>( R_{\text{actual}} )</td>
<td>Actual recycle ratio calculated (negative indicates bypassing)</td>
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### REFERENCES


APPENDIX A

Table A1. Assumptions and results for the pressure drop calculation (around stage 9) using the ‘two-k’ method of Hooper (1981).

<table>
<thead>
<tr>
<th>Description</th>
<th>size (m)</th>
<th>Velocity (m/s)</th>
<th>Re</th>
<th>K1</th>
<th>Kinf</th>
<th>K</th>
<th>V head (m)</th>
<th>Fitting loss (kPa)</th>
<th>Pipe I (m)</th>
<th>Rel Rough</th>
<th>Friction Factor (f)</th>
<th>f iterate</th>
<th>Pipe/fitting loss (kPa)</th>
<th>Pipe/fitting loss (m)</th>
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<td>0.95</td>
<td>381972</td>
<td>0.04643</td>
<td>0</td>
<td>3.6</td>
<td>0.0002</td>
<td>0.0161</td>
<td>0.0154</td>
<td>0.01</td>
<td>0.001363</td>
<td></td>
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</tr>
<tr>
<td>90°Elbow</td>
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Total 3.82 0.39

In order to generate the system curve, the above table was recalculated for a number of flow rates between 0 and 200 t/h.

Figure A1. Measurements used in the calculation of the system head associated with stage 9.
APPENDIX B

Table B1. Assumptions and results for the pressure drop calculation (around stage 9) using the ‘two-k’ method of Hooper (1981) and accounting for cane blockage in the juice tray.

The cane ‘blockage’ was modelled as a 30 mm diameter section of pipe 0.5 m long.
APPENDIX C

Calculation of the $F_0$, the theoretical stage flow rate

To understand and interpret the results of the trial, it is necessary to calculate the expected interstage juice flow rate under no juice recycle conditions. The symbols $F_0$ (Interstage flow), $J$ (Juice carried in the cane between stages), $I$ (Imbibition water) and $B$ (Bagasse) refer to the mass flows (t/h) of juice in each of the four streams. These symbols are shown in Figure C1.

By mass balance:

$$F_0 = J + I - B \quad \text{Eq 1}$$

The theoretical interstage juice flow rate $F_0$ can then be solved by:

$$F_0 = \text{Fibre throughput} \times (SJH + BFW + \frac{Imb\%Fib}{100} - \frac{(100-Fib\%Bag)}{Fib\%Bag}) \quad \text{Eq 2}$$

Equation 2 is similar to that used by Rein and Ingham (1992), where:

- Static Juice Holdup (SJH) = 3 kg juice/kg fibre
- Brix Free Water (BFW) = 0.25 kg juice/kg fibre
- Fibre throughput (t/h) = Cane throughput x Fib%Cane – Mixed Juice throughput x Fib%MJ

The fibre throughput was adjusted to account for fibre leaving the diffuser in Mixed Juice, as mud was not being recycled during the trial. Given the density of juice in the middle of the diffuser is ~1000 kg/m$^3$, the units of $F_0$ may be reported as t/h or m$^3$/h.

![Figure C1. Explanation of diffuser interstage flow calculation.](image)

Rein and Ingham (1992) define $R$ as the recycle fraction (normally expressed as a percentage) required to maximise the actual percolation rate in the diffuser, without causing flooding.

$$R_{\text{required}} = 1 - \frac{F_0}{F_{\text{MPR}}} \quad \text{Eq 3}$$

where:

$F_{\text{MPR}}$ (m$^3$/h) = MPR (m$^3$/m$^2$/min) x Screen Area above tray (m$^2$) x 60.
It is also useful to define $R_{\text{actual}}$ based on the actual flow rate measured by the interstage flowmeter. A negative value of $R_{\text{actual}}$ reflects bypassing.

$$R_{\text{actual}} = 1 - \frac{F_0}{F_{\text{actual}}}$$  

Eq 4

Using data from the CTS laboratory, $F_0$, $R_{\text{required}}$ and $R_{\text{actual}}$ were calculated in Table C1 below.

Table C1: Calculation of $F_0$ and $R$ using equations 2, 3 and 4.

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<th>13/12/2012 (02:00-06:00)</th>
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<td>Cane throughput (t/h)</td>
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<td>122</td>
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<td>Fibre % Cane</td>
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<td>21</td>
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<tr>
<td>MJ throughput (t/h)</td>
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<tr>
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<td>25</td>
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<tr>
<td>Imbibition % Fibre</td>
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<td>150</td>
</tr>
<tr>
<td>Static juice holdup (kg/kg fibre)</td>
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<td>3</td>
</tr>
<tr>
<td>Brix Free Water (kg/kg fibre)</td>
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<td>0.25</td>
</tr>
<tr>
<td>Fibre % Bag</td>
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<td>47</td>
</tr>
<tr>
<td>$F_0$ (m$^3$/h)</td>
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<td>90</td>
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<tr>
<td>MPR (m$^3$/m$^2$/min)</td>
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<td>0.15</td>
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<tr>
<td>Tray area (m$^2$)</td>
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<td>17.6</td>
</tr>
<tr>
<td>$F_{\text{MPR}}$ (m$^3$/h)</td>
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<td>158</td>
</tr>
<tr>
<td>$F_{\text{actual}}$ (m$^3$/h from flow meter)</td>
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<td>$R_{\text{required}}$</td>
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<tr>
<td>$R_{\text{actual}}$</td>
<td>-7%</td>
<td>-13%</td>
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