DIFFUSER PERFORMANCE OPTIMIZATION THROUGH CONTROL OF LIQUID FLOW PATTERNS

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ABSTRACT

The benefits to be gained by controlling liquid flow rates in a stage-wise counter-current cane diffuser are described. A control system to eliminate flooding and keep percolation velocities optimized at all times is proposed. A description of the way control was implemented at Amatikulu and Felixton is given and the results obtained are presented.

INTRODUCTION

Experience with cane diffusers over many years has confirmed theoretical predictions that the degree of preparation is the most important variable affecting extraction. In some cases, however, attempts to produce a finer preparation have led to flooding in the diffuser. This has caused operators to accept sub-optimum preparation to avoid the flooding regime.

Flooding of the cane bed occurs when too much liquid is applied to the top of the bed surface, more than can actually percolate downward between the cane particles. This causes a number of operational problems, including washing of cane out the feed or discharge end of the diffuser in severe cases, but in any event, destroys concentration gradients along the cane diffuser, with a severely detrimental effect on extraction.

In some cases the response to flooding problems has been to move the inter-stage sprays, or weirs closer to the feed end of the diffuser to reduce the degree of recirculation. It has generally also resulted in diffusers being run with lower bed heights, since percolation conditions are more predictable and more stable with lower bed heights. This, of course, has a detrimental effect on extraction by reducing the residence time of cane in the diffuser.

To escape from the flooding regime, diffusers are generally set up such that percolation rates through the cane bed are not as high as they could be, so that flooding does not become a problem under conditions of higher throughput or particularly adverse cane characteristics. Since the rate at which the liquid flows past the particles is an important factor affecting extraction, this invariably means that extraction is not optimized.
This paper attempts to describe the factors which influence percolation velocities and the phenomenon of flooding, and describes a system which has been implemented to control liquid flow patterns at optimum values to maximize extraction.

LIQUID FLOW PATTERNS IN A DIFFUSER

Percolation velocities in cane diffusers

It is necessary to define the difference between percolation rate and percolation velocity. The percolation velocity \( v \) is the downward velocity of the liquid as it moves between cane particles and is measured in m/min. The percolation rate \( U \) is the rate at which liquid is applied to the top surface of the bed expressed as m\(^3\)/min per m\(^2\) of bed area. In general, \( U \) is found to be smaller than \( v \), and the ratio seems to be consistently close to 0.7. This is an indication of the reduced open area for flow in the bed due to the solid material.

The rate at which liquid will percolate vertically downward through the cane bed is a prime operating variable. For this reason a pilot plant investigation to establish the factors affecting percolation was carried out and reported at a previous ISSCT Congress. Results were compared with measurements undertaken on full scale diffusers and the major factors which affect percolation were identified and quantified. This showed that percolation is affected mainly by cane preparation and bed density. More specifically, the maximum percolation rate attainable without flooding, \( U_p \), is dependent on the specific surface or fineness of prepared cane \( S \), and the bulk fiber density \( D \) in the cane bed, by the following equation:

\[
U = \frac{4980}{(SD)^{1/2}}
\]  

(1)

The fiber density itself was found to be a function of the height of the cane bed, with higher packing densities being obtained with deeper beds. In addition, finer preparation represented by smaller particle sizes also led to high fiber densities. The fiber content of cane was also shown to be statistically significant, so that finally the following equation for fiber packing density was obtained:

\[
D = 26.5 \cdot F_c \cdot (0.58Z + 4.3)/(M + 21.2)
\]  

(2)

where, \( M \) is the mean particle size.
These relationships were obtained only with burnt cane of a particular variety (NC0 376). It was clear that differences in cane quality and variety introduced additional variability over and above the factors which were quantified. In addition, the type of cane preparation which is utilized, for instance, whether most of the preparation is done by knife or by shredding, is expected to have a significant effect.

By comparison of pilot plant work with full scale diffuser work, it was found that the percolation velocities measured in full scale diffusers were generally somewhat lower. This was thought to be partly due to the fact that the measurements were undertaken in diffusers which were not flooding, and perhaps were away from achieving maximum percolation rate conditions. In addition, compaction of the cane layer close to the screen due to the effect of the chains can have an effect.

Optimum positioning of sprays

The relationship between bed speed and fiber throughput \( M_j \) is given by the following relationship:

\[
V = \frac{M_j}{(DZW)}
\]

where, \( Z \) is the bed height, \( W \) the diffuser width and \( V \) the bed speed. It is clear from this relationship that the velocity of the cane bed is dictated by the required fiber throughput for a given bed height, but is influenced by fiber packing density.

Referring to Figure 1, if the rate at which liquid percolates vertically downward in the diffuser is \( v \), the time it spends in the bed is \( Z/v \). The point at which the liquid exits from the bottom of the bed is related to the bed velocity. Assuming the liquid exits a distance \( x \) from its point of application,

\[
x = \frac{VZ}{v}
\]

Using equation (3), this becomes

\[
x = \frac{M_j}{(DWv)}
\]

For all the liquid from stage \( N+1 \) to find its way into the \( N \)th tray, the spray advance \( A \) in Figure 1 will be given by:

\[
A = L + x
\]

or

\[
A = L + \frac{VZ}{v}
\]
FIGURE 1: Schematic diagram of stages in a moving bed distiller.

- Bed speed
- Z height
- Spray advance
- Juice flow
- I - N
- N
- I + N
- V
It has been shown that if the liquid is applied as a curtain, as from a weir, the effective point of addition is some extra distance closer to the feed end of the point of addition. This is due to the fact that the overloading of the bed directly below the bed causes liquid to move horizontally toward the feed end where the bed is not saturated with juice. This effect is not evident with sprays which apply liquid uniformly over the area of a stage.

It can be seen from equation (5) that if the crushing rate changes (fiber throughput $M_f$ changes) the point of exit of juice along the diffuser changes. This will increase recirculation if $M_f$ has increased or increase by-passing if $M_f$ has reduced. Likewise if the degree of cane preparation or the cane characteristics change, $D$ and $v$ will change, and again the effective horizontal translation of juice $x$ will change. Also if $v$ changes, the optimum amount of liquid to be applied will change.

**Recirculation and by-passing**

The amount of liquid which is pumped through each stage is determined by the amount of liquid appearing in the stage preceding it. This is illustrated in Fig. 1. Liquid percolating down into stage $N+1$ tray is pumped up to stage $N$. This in turn percolates through the bed of cane. Because the bed of prepared material is moving at a velocity $v$, liquid not only moves down through the bed but is transported in the same direction as the bed of moving material. Liquid appearing at the outlet of stage $N$ is then pumped to stage $N-1$.

The amount of liquid appearing in stage $N$ tray is dependent not only on the rate at which the liquid percolates vertically downward, but also on the velocity at which the bed of material is moving horizontally. It can be seen that if the bed of material is moving too slowly, a large part of the liquid, which should have come out in stage $N$, actually finds its way into stage $N-1$. This phenomenon is known as “by-passing”, where a part of the liquid by-passes stage $N$. The effect of this is to reduce the quantity of liquid coming out in stage $N$, and hence the amount of liquid pumped onto stage $N-1$ is likewise reduced. This can lead to the situation where too little liquid is applied to stage $N$, with the result that inefficient contacting of solid by the liquid occurs. It can be seen that all stages will be affected in a similar manner.

If, on the other hand, horizontal velocity of the prepared cane is increased significantly some of the liquid which should have percolated into stage $N$ is carried past that tray and finds its way into tray $N+1$. Thus some of the liquid which was pumped from tray $N+1$ finds its way back into the same tray. This phenomenon is known as “recirculation”. This means the amount of liquid pumped from tray $N+1$ onto stage $N$ can be increased significantly. Relative to the by-passing case, this situation promotes high liquid application.
rates. If too much recirculation occurs then the amount of liquid applied to stage N can be too high relative to the percolation velocity through the prepared material, so that flooding occurs.

It should be apparent therefore that the degree of by-passing or recirculation can be controlled by moving the point at which the liquid is applied to the top of the cane bed. The ability to do this enables the degree of recirculation to be controlled and hence the liquid flow rates through each stage can be controlled.

Calculation of inter-stage juice flow rates

In the absence of recirculation or by-passing, the theoretical flow rate through a particular stage can be calculated, and is given by:

\[ F_0 = M_x \left[ \frac{1}{100} + H - \left(1.25F_0/F_p\right) \right] \]  

(7)

where:

- \( F_0 \) is the theoretical flow rate through the stage,
- \( M_x \) is the specific flow rate of the cane bed,
- \( H \) is the static juice holdup, and
- \( F_p \) is the percolation velocity.

If this flow rate is too high for the area of the stage under consideration, then some by-passing of the juice must be allowed for to prevent flooding. Alternatively, if the theoretical juice flow quantity is less than the percolation characteristics of the cane, then some recirculation should be introduced to increase the liquid flow rates.

The maximum quantity of liquid which can be applied to a stage is given by the area of the stage, multiplied by the percolation rate. The optimum interstage juice flow rate, \( F \), is given as:

\[ F = WLU \]  

(8)

This flow rate, related to the flow rate in the absence of any recirculation \( F_0 \), indicates the degree of re-circulation or by-passing which is required. If \( F > F_0 \), then recirculation is required to achieve the optimum flow rate; on the other hand if \( F < F_0 \), then by-passing is necessary to reduce the flow to the optimum without any flooding occurring. Fractional recirculation \( R \) is defined as:

\[ R = 1 - \frac{F}{F_0} \]  

(9)

If by-passing occurs, then the value of \( R \) is negative.
For no by-passing or recirculation to occur, the sprays should be located a distance $x$ as given by equation (5) ahead of the center of the tray into which the liquid should percolate. If recirculation is required, the liquid application point should be located closer toward the tray from which it originated. Conversely, if by-passing is necessary, the liquid application should move further away from the tray from which it originated, i.e. more towards the feed end of the diffuser.

Thus the fractional recirculation can also be described by:

$$R = 1 - \left( \frac{A}{L} - \frac{VZ}{V_L} \right)$$

Then 'spray' advance $A$ when recirculation or by-passing is required can be calculated from:

$$A = L (1-R) + VZ/V$$

Because of the relationship between fiber throughput and bed speed (equation 3), this equation can also be written as:

$$A = L (1-R) + \frac{M_e}{(D/s)}$$

Equations (11) or (12) can be used to set up spray advance for average conditions together with equations (7), (8) & (9). Changes in any of the quantities in any of these equations will cause the optimum values of spray advance to change.

**Effect of percolation velocity on extraction**

Research work into the mechanism of extraction showed that preparation is an important variable, since it affects the amount of juice which is made easily available to percolating liquid. However, in a packed bed of cane, high liquid rates past the cane particles are necessary in order to promote the rate of extraction. High liquid flow rates promote extraction by increasing the rate of mass transfer and by improved wetting of cane particles. High liquid rates reduce the amount of sugar which has to be extracted by a true molecular diffusional mechanism, thus increasing the overall rate of extraction. This has been illustrated in the case of the bagasse diffuser by results given in an earlier paper, using a mathematical model.

The mathematical model applied to cane diffusion was used to show the effect of liquid flow rate on extraction, the results of which are illustrated in Table 1.
**FACTORY ENGINEERING**

**TABLE 1. Predicted effect of percolation rate on extraction.**

<table>
<thead>
<tr>
<th>Percolation rate (m³/m²·min)</th>
<th>Extraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.125</td>
<td>97.62</td>
</tr>
<tr>
<td>0.150</td>
<td>98.04</td>
</tr>
<tr>
<td>0.175</td>
<td>98.38</td>
</tr>
</tbody>
</table>

This table shows that if the maximum percolation rate is 0.175 m³/m²·min, then the drop-off in extraction by operating the diffuser at only 70% of maximum flow rate (i.e. 0.125 m³/m²·min) is 0.7%. This effect is likely to be even greater when the average levels of extraction are lower.

It can be seen therefore that the benefits to be gained by operating a diffuser with percolation rates as close to maximum as possible are quite significant. Alternatively, the operation of a diffuser at maximum percolation rates could enable the imbibition rate to be reduced without sacrificing extraction. The model applied to the same conditions as for Table 1 indicates that imbibition rate could be dropped from 350 to 250% on fiber, without sacrificing extraction, providing optimum liquid flow rates are maintained at the lower imbibition rate. This could be of significant advantage to mills who are in a coal-burning situation and can save coal by reducing imbibition rate.

**CONTROL OF LIQUID PERCOLATION RATES**

It is evident from the earlier analysis that a large number of factors will influence the maximum percolation rate. If a diffuser is operating at optimum liquid rates and the cane throughput or the imbibition rate is increased, this will immediately lead to additional recirculation, causing increased liquid pumping rates, with the result that flooding will occur. Alternatively, if the cane throughput is reduced, the amount of recirculation will reduce or the extent of bypassing will increase, thus dropping the percolation rates below optimum.

Apart from the effect of changes in throughput, changes in average particle size or bed density will occur, due not only to changes in the operation of cane preparation equipment but merely due to changes in cane quality or variety from one consignment to the next. As a result, optimum conditions will again change.
These effects can be seen by studying equations (9) to (12). It is clear that there needs to be a continuous control of liquid flow rates if optimum conditions are to be achieved at all times.

Since it is not possible to measure all the individual factors which affect maximum percolation rate, the optimum liquid flow rates on each stage cannot be predicted continuously, and therefore control of flow rate on each stage is not feasible. However, the approach of the system to optimum flow rates can be measured instead by measuring the level of liquid in the cane bed. When flooding occurs, the liquid level rises above the cane bed, leading to the undesirable situation of liquid flowing up and down the top surface of the bed. If liquid rates are too low then the cane bed appears dry. Under optimum conditions a liquid level is seen in the cane bed just a few centimeters below the top of the cane bed itself. This condition gives maximum flow rate through the bed without flooding.

The simplest approach then in optimizing juice flow rates is to measure the liquid level in the cane bed and to regulate flow rates to maintain the liquid in the cane bed at its optimum level.

**Measurement of liquid level in the cane bed**

Many of the conventional methods of measuring liquid levels are not suitable for this application. Sightglasses have the advantage of giving a visual representation of the level but are blocked easily by the fiber and require a secondary device to convert the level into a signal that is usable for control purposes.

A float type device is not suitable as it would rest on the bed of cane, unless the diffuser was in a flooded condition, and hence measure the bed height as opposed to the juice level.

The most successful method of measuring the juice level has been found to be by measuring the hydrostatic head. This has been done at Amatikulu by using a bubbler system. This involves the purging of a small quantity of air into the side of the diffuser and measuring the back pressure, thus obtaining the hydrostatic head. A simpler arrangement has been incorporated at Felixton where an electronic pressure/level transmitter with flush mounting diaphragm has been attached directly onto the side of the diffuser.

There is a pressure profile down the bed and this can be determined by the Kozeny Carman equation. As mentioned earlier, the fiber density is a function of the height of the cane bed, with packing densities increasing as the bed height above it increases.
Figure 2 shows a pressure profile obtained at Felixton. Four transmitters were mounted vertically, at distances of 450, 850, 1,050 and 1,450 mm above the screen, and the outputs were logged. The lower the transmitter is situated in the bed, the more the total juice level in the bed is under-estimated due to a pressure drop down the bed. This effect is non-linear. The effect of compaction lower down in the bed causes the pressure drop to be greatest at the bottom of the bed. In addition, the bottom reading tends to be noisier due perhaps to effects of entrapped air and the close proximity of the screen and the chain.

Typical variations in juice level with fixed spray positions before the installation of control in the Felixton diffuser are seen in Figure 3.

Methods of controlling flows

It is generally not possible to control the liquid flow to each stage using a control valve. A control valve is useful in reducing flows down to the right level when there is surplus juice in the tray. However, the installation of a control valve in the line will not be able to increase flows when there is a call for high juice flow rates. A further disadvantage of a control valve on a throttling application is that it can lead to liquid levels building up in each tray under the diffuser, which has the detrimental effect of increasing the overall retention time of juice in the system.

Another option is to install overflow vents at the level of the cane bed, such that any surplus liquid on the top of the surface due to flooding would simply run sideways off the bed and not break down the concentration gradient along the length of the diffuser. This however would not work well on very wide diffusers (e.g. 12 m wide diffuser at Felixton), and suffers from the same disadvantage as a control valve, in that it can cope with liquid rates that are too high, but cannot promote higher rates when conditions call for them.

The approach adopted in controlling flow has therefore been to adjust the point of application of liquid on each stage. When there is a need to adjust the displacement between a particular pump and optimum spray position because of changes in variables shown in equations (11) or (12), this can be achieved by varying the point of application of liquid onto the bed.

This was first carried out successfully at the old Empangeni Mill, where the sprays were modified to incorporate an adjustable flap. A similar arrangement was subsequently installed at Amatikulu Mill. A sketch of this is given in Figure 4. By varying the position of the flap the juice application point can be varied within a range of about 1.5 m.
FIGURE 2. Liquid level measured by pressure transmitters at different heights in diffuser bed.
FIGURE 3. Typical variations in the liquid level in the dilution bed in the absence of control.
A similar arrangement is possible for juice overflowing a weir. In both these cases a solid curtain of liquid is applied at one point on the bed surface.

A different and simpler arrangement has been incorporated on the sprays at Felixton. This involves the installation of an angle iron which can be rotated below the spray pipe, thus deflecting the juice forwards or backwards depending on the rotation of the angle iron. A sketch of this device is also shown in Figure 4. The advantage of this system is that it requires less force to rotate the angle iron and sprays the juice over a wide area, thus reducing the immediate juice overload at the point of application. Measurements with this system indicated that it enabled the liquid to be sprayed a full stage backwards from the mid-point of the spray itself (stage length is about 4 m per stage).
FIGURE 5. Amatikulu extraction results.

RESULTS OF INTERSTAGE JUICE FLOW RATE CONTROL

Experience at Amatikulu

Figure 5 shows how extraction at Amatikulu has improved over the last ten years. Over this time period, fiber throughput rate, moisture % bagasse and Preparation Index (PI) have all remained roughly the same, showing only minor variations from one season to the next. Average values of these quantities are 52 tons fiber/h, 52% moisture in bagasse and a PI of 92-93. When the diffuser was commissioned in 1974/75 the bed height was run at about 1.6 to 1.7 m. Because flooding conditions were experienced, the bed height was steadily reduced to about 1.2 m. Extraction improved, since extraction was less affected by flooding, even though the residence time of cane in the diffuser reduced as a consequence. At that time, the only way of controlling flooding was to turn a number of the spray pumps off where flooding was at its worst. This could not always be done, because the point of application of the water had to be at the very bottom of the diffuser to keep the bed from clogging.

A new design of spray was installed in 1983/84 which was less prone to blocking. Positioning of the sprays was calculated using the equations given earlier. Experimentation started with flaps positioned below the sprays to vary the point of application. Over the next few seasons, adjustable flaps as shown in Figure 4 were installed. This enabled operators to get out of flooding problems when they occurred, and to increase liquid flow rates when the bed
appeared too dry. This had a dramatic effect on extraction, increasing to over 98% since flooding was no longer a constraint. It also enabled higher imbibition rates to be applied as shown in Figure 5, which also helped achieve high extractions. Previously increasing imbibition rates merely aggravated flooding. Since then bed levels have been able to be increased, without causing percolation problems. Presently bed heights of about 1.5 m are being recorded. Over the last two seasons, 6 of the 16 stages in the diffuser have had spray flaps adjusted by automatic controls, based on measuring, liquid level in the bed using a bubbler.

Extraction improvements in the latest season have been largely due to “fine tuning” the shredder, thus improving preparation. The variable throw sprays in the diffuser have enabled the finer preparation to be accommodated. Otherwise the normal consequence of finer preparations is to lead to reduced percolation velocities and then flooding.

Experience at Felixton

After the 1990 season the sprays on one of the two diffusers at Felixton (each nominally 300 tons/h units) were re-positioned to increase the amount of recirculation possible. This was done as the sprays were being run almost continually in the “full recycle” position and juice levels in the bed were low. This was a reflection of the fact that the fiber throughput was below design, and resulted in the percolation rates not being optimal.

In addition, the sprays of this diffuser have recently been fully automated. The cost of this was justified on the grounds that the expected reduction in imbibition would result in a coal saving to Felixton that would pay for installation within a quarter of a season. Figure 6 illustrates the shows the juice level measured in a stage relative to the setpoint.

The error causes a change to the spray position to try and control this level. This system is capable of keeping the liquid level at the desired position, but unfortunately it is too early to have done a full evaluation. The effect on extraction will be evaluated in the following season.

CONCLUSIONS

The way in which the point of application of inter-stage juice in a cane diffuser affects juice flow rates has been established. The pivotal factor involved is downward percolation velocity, which is affected by cane preparation, cane quality and variety, and fiber packing density.
It has been shown that varying the point of application of juice enables the diffuser performance to be optimized, avoiding flooding problems. This enables percolation rates to be maximized, and bed heights to be increased, both of which lead to a gain in extraction. Experience at Amatikulu and Felixton mills has shown the advantages to be gained from controlling the point of application of stage juice, using relatively simple control systems.

ACKNOWLEDGMENTS

Practical development of the principles reported here was spearheaded at Amatikulu, largely due to the efforts of Cecil Hooper and Jan Maleta.

Nomenclature:

A  Spray advance or displacement between pump and spray (m)
B  Bulk fiber density of cane bed (kg fiber/m³)
C  Liquid flow rate (m³/min)
D  Liquid flow rate with no recirculation (m³/min)
E  Fiber in bagasse (%) (see below)
F  Fiber in cane (%) (see below)
H  Static liquid holdup in cane bed (kg/kg fiber)
I  Imbibition % fiber
J  Tray length in moving bed diffuser (m)
K  Mean particle size (mm)
L  Fiber throughput rate (kg fiber/min)
M  Number of stage tray
N  Fractional recirculation of liquid
O  Specific surface of shredded cane (m²/kg)
P  Percolation rate (m³/m² min)
Q  Percolation velocity (m/min)
R  Bed velocity of moving bed diffuser (m/min)
S  Height of cane bed (m)
T  Density of juice (kg/m³)
U  Horizontal displacement of juice (m)
V  Density of juice (kg/m³)
W  Width of diffuser (m)
X  Percolation rate (m³/m² min)
Y  Percolation velocity (m/min)
Z  Percolation rate (m³/m² min)

REFERENCES


L'OPTIMISATION DE LA PERFORMANCE DES DIFFUSEURS PAR LE CONTROL DE LA CIRCULATION LIQUIDE

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RESUME

On décrit les avantages réalisés par le contrôle de la circulation liquide dans les diffuseurs contre-courants, pour la canne. On propose un système de contrôle qui élimine le “flooding” et qui garde la vitesse de percolation à une valeur optimale. Ce système a été appliqué à Amatikulu et à Felixton. On donne les résultats obtenus.

TRABAJO DE DIFUSOR-MEJORAS A TRAVÉS DEL CONTROL DEL FLUJO DE LIQUIDOS

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RESUMEN

Los beneficios obtenidos al controlarse los flujos de los líquidos en un difusor de caña de contracorriente son descritos. Un sistema de control que elimina el desborde y mantiene la velocidad óptima de percolación todo el tiempo es propuesto. Una descripción del sistema de control implantado en Amatikulu y Felixton y los resultados obtenidos son dados a conocer.

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