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MONITORING JUICE HOLDUP IN A CANE DIFFUSER BED USING ELECTRICAL CONDUCTIVITY – EVALUATION ON A LABORATORY SCALE

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Abstract

The control of percolation within the bed of shredded cane is a critical aspect of the design and operation of cane diffusers. The extraction of an operating diffuser can be optimised by the suitable setting of adjustable sprays to alter the percolation rate to maximise the juice holdup within the cane bed. Without an online measurement of juice holdup within the cane bed, the adjustment is conventionally done by operators using visual observation, judgement and experience. There is clearly an incentive to operate substantially below the maximum percolation rate to avoid the possibility of flooding and thus the best possible extraction performance will seldom be achieved.

An on-line measurement of juice holdup within the cane bed creates the opportunity to implement feedback control of juice holdup by automatic adjustment of diffuser sprays – avoiding the inevitable compromise of manual operation. Previous work using a pressure measurement on the side of a diffuser as an indicator of juice holdup showed some potential but two local installations failed to gain the confidence of operating staff and have fallen into disuse.

This work describes the evaluation of electrical conductivity through the cane bed (from top to bottom) as a measure of the juice holdup within a cane bed. Tests were done in the laboratory on a glass column diffuser. Suitable instrumentation and data logging allowed on-line measurement of electrical conductivity and liquid holdup within the cane bed. The prevailing percolation rate could be measured and logged using a simple manual intervention. The results confirmed the close correlation between percolation rate and juice holdup and also the potential of electrical conductivity to be used as an indicator of juice holdup within the cane bed.

Key words: Diffuser, hold-up, flooding, conductivity, extraction

Introduction

The basics of the operation of a standard moving bed cane diffuser are well described in the text on cane sugar engineering by Rein (2007). It was Rein who did pioneering fundamental work on understanding the mechanisms involved in diffuser operation based on both pilot and full scale testing and detailed mathematical modelling (Rein, 1972). Rein's original work was on bagasse diffusers (i.e. a diffuser preceded by a first mill) and he subsequently collaborated (Love and Rein, 1980) on work that investigated the behaviour of cane diffusers (fed with shredded cane without any preceding mill, now regarded as the standard extraction plant in South African sugar factories). This work also extended to modelling and measuring the juice flow distribution within the cane bed of full scale diffusers.

Central to understanding the behaviour and performance is the link between juice flow through the bed and juice holdup within the bed, as summarised in the points below:

1. There is a maximum rate at which juice can be applied to the surface of the bed without the liquid forming a level on the top of the bed (termed flooding).
2. Below this rate (termed the maximum percolation rate), the liquid drains freely, but some liquid is held up within the bed. The quantity of liquid held up within the bed depends on the flow rate with higher flow rates corresponding to higher liquid holdup.
3. The extraction is maximised if the juice flow is at the maximum percolation rate. The mechanism is not entirely clear but is almost certainly a combination of two factors; improved contact between the percolating juice and the cane particles due to the higher quantity of juice held up within the bed, and improved mass transfer between the cane particles and the percolating juice due to more mixing, turbulence and shear at the higher juice velocities.
4. If juice is applied at a rate higher than the maximum percolation rate in an operating, multi-stage diffuser (rather than the test conditions of a pilot column) the flooding causes juice to flow horizontally across the surface of the bed disrupting the multistage counter-current operation that is essential for good extraction.

Diffusers are conventionally designed with a stage size sufficiently large so that when operated, the juice flow proceeds in a stage-wise counter-current manner (with no bypassing or recycling on each stage) and the percolation rate will be below the rate at which flooding occurs. Ensuring that this pure, stage-wise percolation occurs requires that the sprays adding the juice to the surface of the bed are correctly positioned. To maximise extraction, the interstage flow rate needs to be increased to as close to the maximum rate as possible without flooding. Rein (2007) describes how this is achieved by adjusting the position of the juice sprays so that a degree of recycling occurs within each stage.

The percolation rate at which flooding occurs is known to vary with cane variety and degree of preparation (Loubser and Barker, 2011). This means that, to maximise extraction, a diffuser should ideally have adjustable sprays and a means of estimating how close the prevailing percolation rate is to the flooding rate. Without an online measurement of juice holdup within the cane bed, the adjustment is conventionally done by operators using visual observation, judgement and experience. There is clearly an incentive to operate substantially below the maximum percolation rate to avoid the possibility of flooding and thus the best possible extraction performance will seldom be achieved.

Rein and Ingham (1992) described the design of adjustable sprays and the use of pressure sensors on the side wall of the diffuser to estimate the level of juice held up within the cane bed. This use of pressure to estimate level within the bed relies on an increasing fibre density towards the bottom of the bed and/or a substantially greater pressure drop for juice flow through the diffuser screen. The combination of both an on-line measurement of the holdup within the bed and actuated variable sprays allowed the implementation of feedback control to maintain the juice level close to its maximum value. Some success was achieved as evident from results presented in the paper but the data were particularly noisy and two local installations failed to gain the confidence of operating staff and have fallen into disuse. A major concern was always that the level measurement was only representative of what was happening close to one wall of the diffuser (of the order of 1 to 10 cm) whilst the full width of the diffuser could be as much as 9 m.

Loubser and Jensen (2015) reported on both mathematical modelling and laboratory measurements of juice flow within a bed of shredded cane. They reported that the static pressure in the bed (that would be measured by a pressure transmitter on the side of the bed) depends on the distribution of permeability within the bed. The pressures that they measured were less than ±15 mm of water gauge from atmospheric. They attributed these small values as due to minor variations in the characteristics of the cane bed and observed that it would be difficult to use pressure as an indicator of juice holdup. It is possible that the increased wall effects of their laboratory equipment restricted bed packing and made pressure measurement less suitable than it might have been on full scale equipment. Despite this reservation, their work does show that using pressure as an indicator of juice holdup within the bed relies on a rather subtle second order effect of the variation in permeability within the cane bed.

Electrical Conductivity as a Possible Measure of Juice Holdup

It is well known that cane juice is electrically conductive due to the presence of inorganic impurities extracted from the cane. Matthesius (1979) undertook some on-line measurements of juice conductivity on adjacent stages of an operating diffuser and proposed that this approach could be a useful method for monitoring diffuser performance.

It was not unreasonable to suspect that if it were possible to measure the conductivity of the wetted cane bed, this would increase as the quantity of (conductive) cane juice held within the cane bed increased. The maximum conductivity, depending on the conductivity of the juice itself, would be achieved when all the voids between the cane particles were filled with juice. This strategy has the potential to be far more representative of the juice holdup within the bed than a pressure measurement on the side of a relatively wide diffuser bed.

This concept was the driver for the laboratory tests described below, which were conducted on the premise that the technique would need to be able to show good potential under closely controlled laboratory conditions if it was to have a chance of being a viable technique for monitoring the behaviour of full scale diffusers.

Laboratory Setup

The batch column diffuser used for the laboratory testing is shown in Figure 1.

The components of the laboratory batch diffuser column and its associated instrumentation are best described using the schematic representation depicted in Figure 2.

The major components of the batch diffuser column are:

1. Glass column
   The shredded cane was placed in a cylindrical glass column with an internal diameter of 302 mm. At the base of the column, to retain the shredded cane, was a piece of standard perforated plate as used in full scale diffusers (18 mm holes on a triangular pitch with a 40 % open area). The perforated plate was mounted just above a solid plate with an outlet nozzle to ensure that the liquid left the column in a relatively narrow stream. After the shredded cane had been added to the column, a second perforated plate, identical to the one at the base, was added to the surface of the cane. The bed height between the top and bottom plates was approximately 1 200 mm. Insulated cables were attached to each of the perforated plates and connected to a conductivity transmitter. A simple perforated bowl distributor was fitted to the top of the column to ensure that the juice pumped into the top of the column was evenly distributed over the top of the bed.
2. Suction tank
   A suction tank was positioned below the juice outlet on the base of the column. The suction tank was mounted on an electronic scale with a digital serial output allowing it to be connected to a personal computer.

Figure 1. Batch diffuser column used for laboratory testing

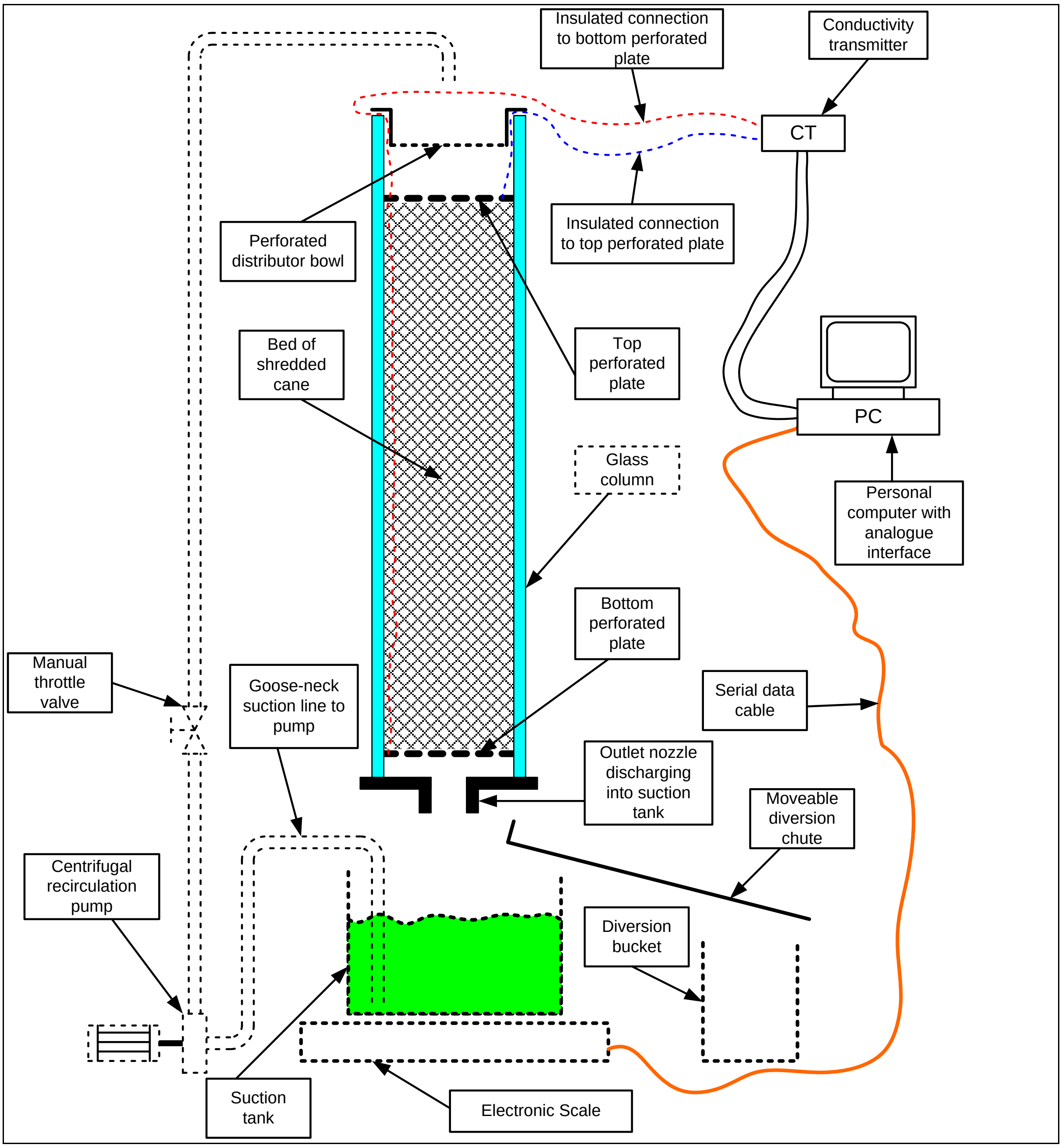

Figure 2. Schematic diagram of diffuser column and its associated instrumentation

3. Centrifugal Pump and Piping
   A centrifugal pump was positioned on the floor adjacent to the suction tank. A "goose neck" piping arangement was used for the suction line to the pump so that there was no mechanical connection to the tank that could affect the measurement of the mass of the tank and its contents. The discharge line from the pump, running to the top of the column, was fitted with a manual throttle valve so that the juice flow into the top of the column could be adjusted by throttling the valve.

4. Diversion chute and diversion bucket
   To allow measurement of juice flow through the bed during operation, a simple "diversion chute" arrangement was provided to enable the juice leaving the column to be diverted into a diversion bucket for a short period. At the end of the short

measurement period, the diversion chute could be removed and the contents of the diversion bucket could then be returned to the suction tank. This flow measurement technique is described in more detail in the section describing the analysis of results.

5. Conductivity transmitter
   A variable range conductivity transmitter, previously designed and constructed for undertaking tracer tests on full scale diffusers, was connected to the leads from the perforated plates that were positioned at the top and bottom of the cane bed respectively. The conductivity transmitter provided an output voltage signal that was proportional to conductivity. The conductivity transmitter was calibrated using a standard decade resistance box so that the voltage signals could be converted into conductance reading in mhos (ohms $^{-1}$).

6. Personal computer with analog interface
   A personal computer fitted with an analog input card was used to display and record both the conductivity signal from the conductivity transmitter and the signal from the electronic scale. Purpose written software was used to read data from both the analog input card and the serial interface port to which the electronic scale was connected. The data were logged to disk at fixed intervals (every five seconds) in a text file format that could be subesequently imported into a spreadsheet for analysis.

Test Procedure

The test procedure used in this work was relatively simple because the primary intention was to test the viability of the use of conductivity across bed as a measure of juice holdup rather than provide definitive data on the percolation behaviour of particular samples of cane.
The basics of the test procedure were as follows:

- Add shredded cane to the column by hand, filling the column to the maximum possible height of approximately 1 200 mm (knowing that some compaction would take place once the cane was wetted with percolating water/juice);
- Place perforated plate on top of cane bed;
- Place the distribution bowl in the top of the column and direct the outlet pipe from the circulation pump into the distribution bowl;
- Fill suction tank with water;
- Start data logger;
- Start centrifugal pump and adjust the flow into the top of the column by throttling the valve on the discharge side of pump whilst ensuring that the bed does not flood;
- Set the juice flow at a number of different flows by adjusting the position of the throttle valve, from low flows up to the maximum flow at which flooding occurs, leaving the valve in each position for sufficient time at each setting to allow conditions to stabilise at that flow;
- Once the conditions have stabilised at each flow, perform a flow measurement test by using the diversion chute to divert the flow from the bottom of the column into the diversion bucket for a period and then subsequently empty the contents of the diversion bucket back into the suction tank;
- During the a test, the cane bed will normally compact to some degree. To be able to compensate for the effect of this on the conductivity reading (i.e. the two perforated plates moving closer together) manual measurements of the height of the bed need to be recorded at intervals throughout the test; and
- Once sufficient data points have been collected, shut the throttle valve and stop the pump. Allow the column to drain completely before stopping the data logging and ending the test.

An example of the data collected during a representative test is shown in Figure 3.

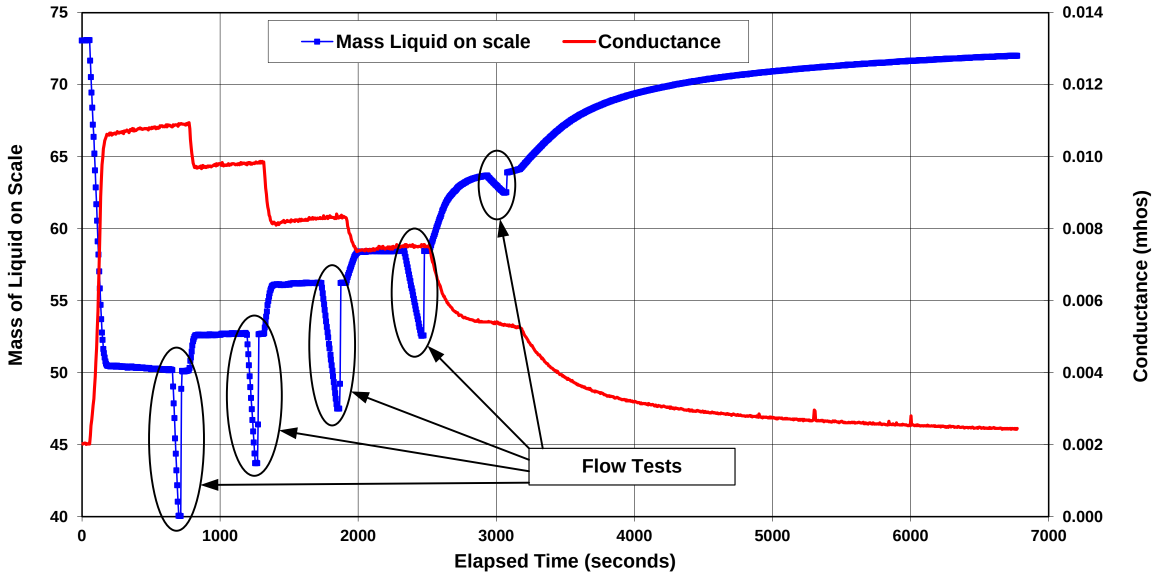

Figure 3. Plot of data collected during a typical test run

The details of how a flow test is conducted are indicated in Figure 4 where an expanded portion of the trend data shown in Figure 3 is annotated to show how each of the various steps in the flow test can be deduced from the logged data.

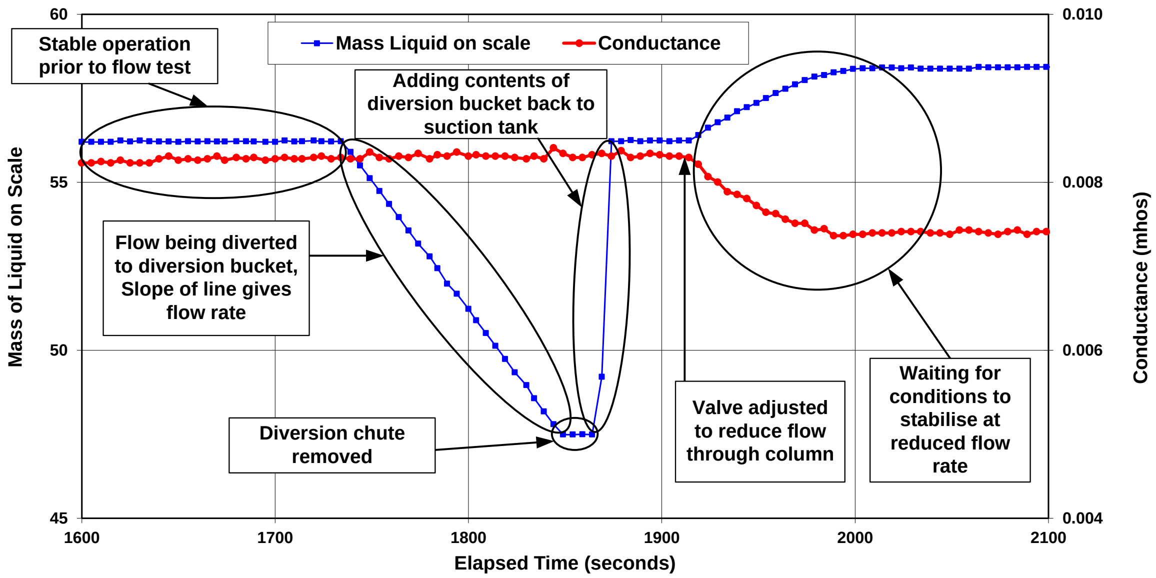

Figure 4. Segment of test run explaining details of a flow test

Analysing Logged Data from a Test

To analyse the logged data from a test, it was necessary to identify the portions of the data as indicated in Figure 4. From each period where the flow from the column was being diverted into the diversion bucket it was possible to calculate a rate of change in mass with time to give the prevailing flow rate out of the column. Dividing this by the cross-sectional area of the column it was possible to calculate a percolation rate (superficial velocity) conventionally expressed as m/min.

To track the quantity of juice held up within the bed it was necessary to exclude the periods of data when the flow tests were being conducted. This constitutes all those periods when any juice was present in the diversion bucket. The quantity of juice held within the bed could then be calculated by the difference between the prevailing mass on the scale at any instant and the mass on the scale when the bed was fully drained (based on the simple principle that if the juice was not in the suction tank it must have been held up within the bed). By using the scale reading at the end of a test, when the bed had fully drained, instead of the mass on the scale at the start of a test as the mass associated with a fully drained bed, it was possible to accommodate for the quantity of juice that was held within the pump and its associated piping.

It is possible to turn the conductance readings (in mhos) recorded from the conductivity transmitter into more universally comparable conductivity measurements (in micromhos/cm). This was done by filling the empty glass column with liquid of a known conductivity and then determining an effective “cell constant” for the column as a function of the distance between the two perforated plates. This then made it possible to compensate for any packing of the bed during a test by using the manually recorded distance between the perforated plate to calculate the conductivity of the cane bed at each instant. By sampling and measuring the conductivity of the circulating juice, it was possible to present the prevailing conductivity of the bed as a percentage of the conductivity of the circulating juice.

Results from Analysis of Logged Data

An analysis of the data shown in Figure 3 yields the relationship between percolation rate and juice holdup shown in Figure 5. These results clearly confirm the relationship between juice holdup and percolation rate, with higher percolation rates corresponding to an increased holdup of juice within the bed.

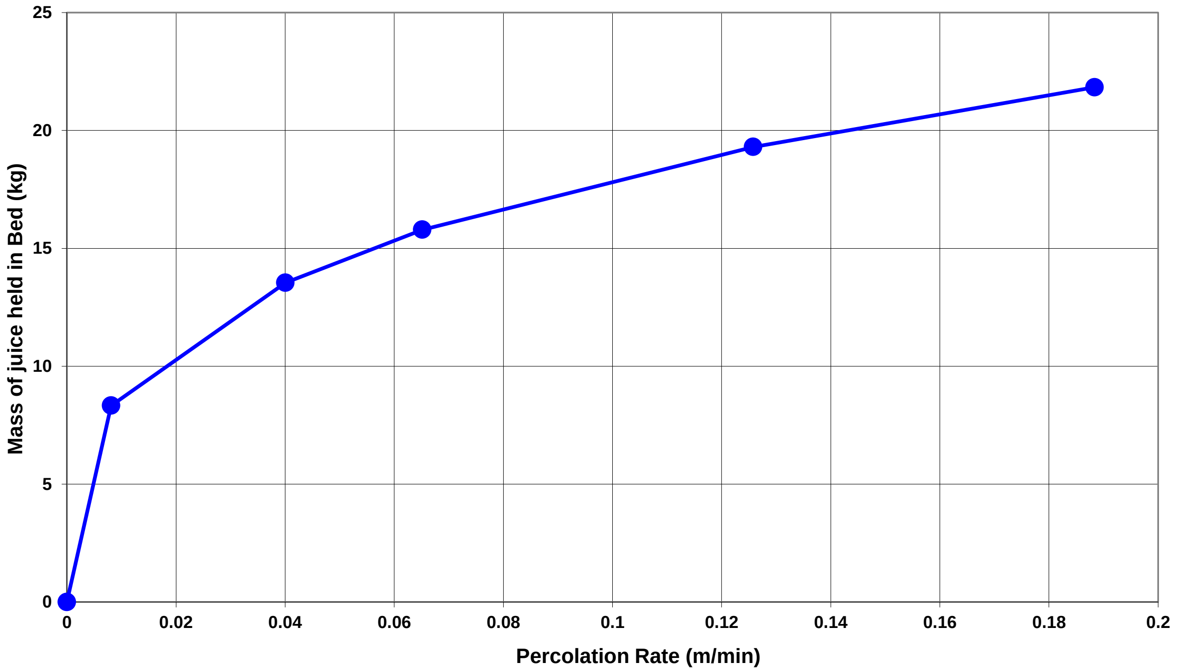

Figure 5. Variation of juice holdup with prevailing percolation rate

Interestingly, the data in Figure 5 show a nonlinear relationship between juice holdup and percolation rate with the holdup being less sensitive to change in percolation rate at higher percolation rates than it was at low percolation rates.

Using the balance of the data (i.e. excluding the periods when the flow tests were being conducted), it is possible to plot a graph of juice holdup against the conductivity of the bed (expressed as a percentage of a theoretical maximum conductivity of a column filled only with juice). This is shown in Figure 6. The data points along the horizontal axis, relating to zero liquid holdup within the bed, are points that have been excluded from consideration because they are associated with flow tests. Figure 6 has been annotated to show the clusters of points when the column was operated at a constant percolation rate and the juice holdup remained essentially constant. The large numbers of points at these indicated positions cannot be properly seen as many of the points lie on top of each other.

Looking back at the raw data in Figure 3, there was a slow increase in the conductivity readings during most of these periods. This may have been due to an increase in temperature with time due to the power input from the pump, but this cannot be confirmed as temperature was not monitored during the tests (which were all conducted at laboratory room temperature).

A striking feature of the data presented in Figure 6 is the near linear relationship between juice holdup and conductivity, regardless of whether the column was being operated stably at a fixed percolation rate, or was in transition between two percolation rates. Particularly interesting was that approximately the same linear relationship extended to the period when the circulating pump was switched off and the column was allowed to drain (juice holdups below about 7 kg). This means that the top perforated plate maintained an effective electrical contact with the top of the cane bed without needing to be wetted with a constant flow of juice over it.

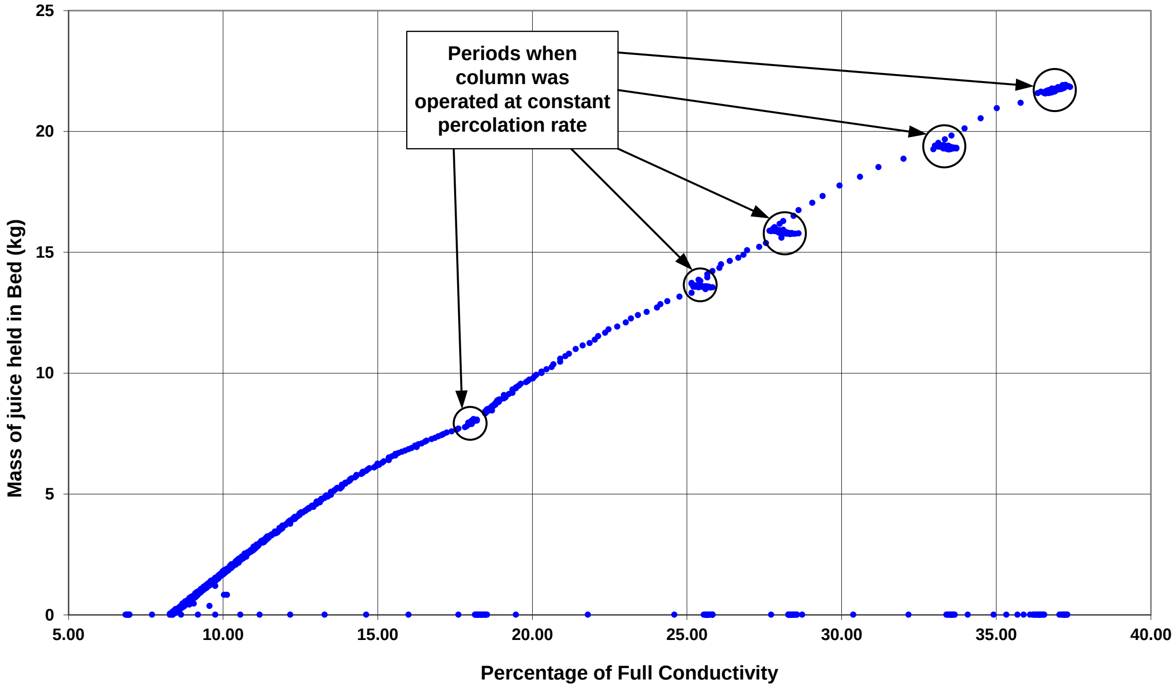

Figure 6. Relationship between juice holdup and bed conductivity

A range of other tests was conducted, showing very similar results to those presented here. It may be possible to extract extra information from a more detailed analysis of all the results but there is a very clear indication from the results presented here that conductivity measured from the top to the bottom of a cane bed (referenced to the conductivity of the percolating juice) has the potential to provide a signal that correlates well with quantity of juice held up within the cane bed.

The issue of how this type of conductivity measurement can be implemented practically on a full scale diffuser and used to automate the adjustment of the diffuser sprays in an attempt to maximise extraction is clearly not a trivial task, but the results presented here indicate that this is a goal worth pursuing. The bed conductivity measurements would need to be referenced to the conductivity of the percolationg juice. It would then make sense to install juice conductivity and temperature measurements on every stage. This would provide both a temperature compensated conductivity profile and a temperature profile along the diffuser to be used as a further tool for assessing diffuser operation and performance (as per the suggestion of Matthesius (1979). The level of the top of the cane bed would also need to be measured (as is currently done in some diffusers). The level can be measured at a number of points across the diffuser at a point along the length of the diffuser just after the cane has been wetted and compacted. The level at all other points down the length of the diffuser can be inferred (using distance along the bed and the bed speed) from the bed level when the portion of the bed had passed under the level sensors.

Conclusions

- A simple lab setup provided a convenient means for investigating the potential of using electrical conductivity across a percolating cane bed.
- The results confirmed the strong dependence of juice holdup within a cane bed on the percolation rate through the cane bed.
- The results showed a strong, approximately linear correlation between conductivity of a cane bed (measured from top to bottom and related to the conductivity of the percolating juice) and juice holdup within the cane bed.
- The success of this measurement technique, although only demonstrated under relatively closely controlled laboratory conditions, provides an incentive for investigating how it might be implemented on full scale diffusers and used as part of a strategy for automatic control of adjustable diffuser sprays to maximise extraction.

Acknowledgements

Results presented in this paper were obtained over ten years ago and kept with the intention of reporting them once it had been possible to test the potential of the technique on a full scale.
A significant part of the experimental work was done by the late Gerald Schumann and looking back at the results, they clearly show the meticulous attention to detail that is a hallmark of the excellent sugar technology research that he undertook over many years.
A recent collaboration with a graduate student (Diana Angel) from the University of São Paulo in Brazil has enabled a first investigation of the technique to be conducted on a full scale diffuser of the Tongaat Hulett design at the Maidstone factory (Angel et al 2017).

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