

REFEREED PAPER

CANE DIFFUSER TRACER TEST: DEVELOPMENT OF EQUIPMENT TO TUNE PERFORMANCE

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Abstract

Tracer testing is a commonly used technique to determine the flow and percolation parameters required to configure juice distribution trays in a diffuser for efficient operation. Sodium chloride has become the preferred tracer medium for diffusers since the cost is low and, unlike other tracers such as lithium or fluorescent dye, it can be quantified in real time using conductivity change measurements.

Early workers used commercial conductivity probes but these were expensive and a challenge to integrate into a convenient data acquisition system. In the previous two decades, the Sugar Milling Research Institute NPC (SMRI) developed a custom-made system which used probes suspended in containers of overflowing juice and linked to a central data collector using long cables. Variations in resistance as well as cable breakage meant that data were not always reliable.

This paper describes the basic principles of operation and capabilities of a new conductivity tracer test system that has been developed by the SMRI. Flow-through conductivity cells with a temperature measurement are used. Each conductivity cell is connected to an outstation which in turn has a wireless link to a central base station. The base station is connected to a notebook computer through a USB port. Custom software was used to control the measurement and data acquisition process. The temperature compensated conductivities can be displayed in real time. The results of the tracer test (percolation velocities and angles) can be calculated immediately after completion of the test, allowing rapid feedback on the diffuser performance.

Keywords: diffuser, tracer test, percolation, conductivity, flooding

Introduction

The operation of a diffuser requires a balance between the degree of wetting of the cane and the tendency for the diffuser to flood. If too much juice is retained in the diffuser, flooding occurs causing uncontrolled mixing of the juice and, if the bed is too dry, the extraction will suffer. To achieve this balance, several interrelated factors need to be tuned. Some of these factors, such as chain speed and throughput, are routinely changed during normal operation. The factory supervisor also has the possibility of changing the shredded cane characteristics by altering settings in the preparation plant. Some parameters, however, are fundamental to the design of the diffuser itself and cannot be changed after construction. The length of each stage, or tray, for example, is determined using factors such as the dispersion characteristics of the flow through the cane. Studies in this area have been reported by Love and Rein (1980) who derived a model for dispersed plug flow. Dispersion coefficients could be determined by

fitting this model to experiment data. Knowledge of the dispersion characteristics is essential for the choice of tray dimensions during the design process.

A parameter that can be altered to suit changes in cane characteristics over time is the stage advance, that is, the distance between the point where the juice is added to the top of the cane bed and the tray where the juice is expected to leave the bottom of the bed. To determine the required advance, an estimate of the percolation velocity or mean residence time is required. Since these quantities depend on complex fluid mechanics through cane with variable physical characteristics, tracer testing provides a practical method of determining the flow characteristics through the cane bed.

What is tracer testing?

A substance, which can be detected by some means, can be introduced into a flow to determine the route taken by that flow. In a sugar factory, the substance could be lithium ions, which do not naturally occur in cane. An atomic absorption spectrometer is used for measuring the concentration of lithium, an off-line procedure which is associated with time delays between the test and availability of results. Several other substances such as magnesium ions, radioactive iodine and fluorescein have also been used for tracing flows in various equipment (Rouillard and Smith, 1981).

In the case of diffusers, it is convenient to use sodium chloride. This produces a change in conductivity which may be detected and plotted in real time. However, steps have to be taken to correct for the background conductivity that naturally occurs in the juice.

The tracer test is performed on the diffuser while the diffuser is operating at steady state under the correct operating conditions. That means, phenomena such as flooding and juice build-up in the compartments below the diffuser are avoided for the duration of the test.

Fifty kilograms of common salt (sodium chloride) is dissolved in 200 litres of hot water. At the beginning of the test the salt solution is introduced rapidly onto the tray from where flow into the direct compartment would be expected. This is usually done by injecting the solution into the inlet side of the recycle stage pump (R_1), although this may vary depending on the design of the diffuser. Typically, as shown in Figure 1, the resulting change in conductivity is measured at five consecutive trays: the direct tray (D), first and second bypass trays (B_1 and B_2) and first and second recycle trays (R_1 and R_2).

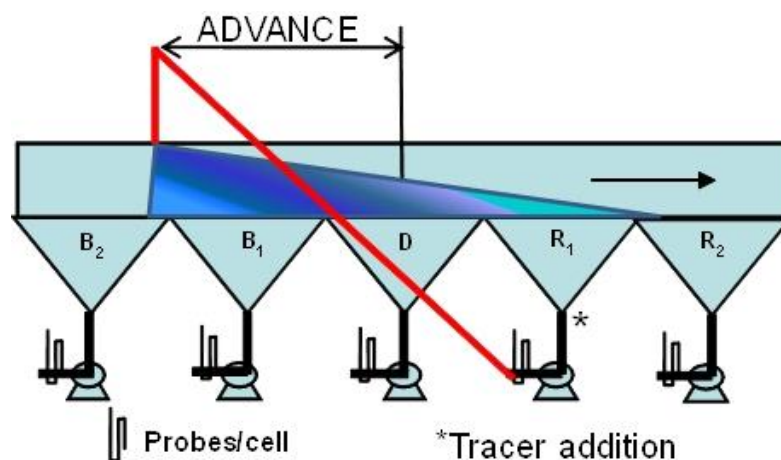


Figure 1. Tracer addition and sample points.

Conductivity tracer equipment

Conductivity transmitters and associated modules

Industrial conductivity instrumentation such as that used by Love and Rein (1980) can be used for tests. Either manual recording of the conductivity values can be done or other electronic modules could be added to link the system to a central data logger. If a manual system is used, the labour input to the test is high, resulting in a limitation in the number of data that can be acquired. The use of discrete function modules to link to a data logger can result in a bulky system with high power consumption.

Equipment developed at SMRI using I²C

The special purpose equipment described by Gooch *et al.* (1999) was developed by the SMRI to be a robust, self-contained system. The conductivity was measured using probes consisting of parallel stainless steel electrodes about 40 mm long and 40 mm apart. A cable was laid from the central data capture electronic box to each of the probes. A transformer provided isolation between the probe and the electronics to eliminate stray voltages. The communication with the computer was done using Inter-Integrated-Circuit (I²C) communication implemented through the printer port on the computer.

Specialised wireless connected system

The I²C system required a computer with a printer port. Since printer ports are rarely supported on modern computers, a change was essential. This was also the opportunity to embrace the move towards wireless technology. A system was developed which uses wireless communication between the computer and the conductivity probe. This eliminated the need to roll out cables to each of the test points. More of the computing power of the computer was thus exploited to facilitate rapid preparation of preliminary results.

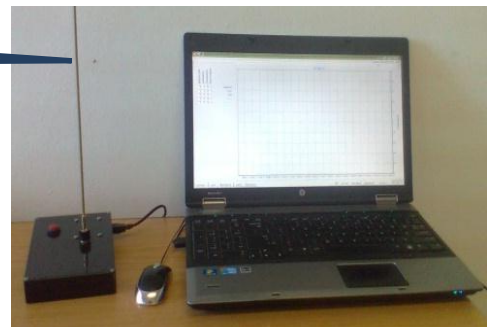
Wireless tracer test equipment

Data acquisition hardware

The three elements of the wireless system are shown in Figure 2. A sample of juice is directed through each of the flow-through cells where conductivity and temperature are measured. The signal conditioning, digitising of the conductivity signal and data transmission are handled by the battery powered outstations. The outstations communicate to a single base station. The base station communicates with the computer through, and is powered by, the computer's universal serial bus (USB) port.



Outstation and conductivity cell



Computer and base station

Figure 2. Elements of wireless system.

Conductivity

The conductivity circuit uses the cell as the resistance in a resistance-capacitance (RC) complementary metal oxide semiconductor (CMOS) inverter oscillator. A microprocessor is used to count the period of the oscillator using a crystal to generate the time base. The resulting count is proportional to the circuit conductivity or inversely proportional to the circuit resistance. This technique avoids the need for an analogue to digital (A/D) converter and the need for a regulated voltage or current source.

The circuit resistance consists of the cell resistance in series with the internal resistance of the data acquisition system. Known resistances ranging from 500 Ω to 2 k Ω were connected in place of the cell and the internal resistance determined. The count representing this resistance was determined using linear regression and was stored on-board each of the outstations. This value could then be requested by the computer and used in the conductivity calculation.

Conductivity cell

Typically a small side stream is extracted from the diffuser juice sample point for measuring conductivity. Historically, a plastic bottle was used with a probe consisting of two stainless steel electrodes (Gooch *et al.*, 1999). A flow-through cell was developed consisting of a U-shaped polypropylene pipe to ensure that the electrodes are always in contact with juice during the test. Two standard 22 mm (nominal 1 inch) stainless steel nipples are used as electrodes. Efforts were made to keep the cell constant close to 1 cm. This will keep the current requirement in the sensing circuit within acceptable limits to ensure adequate battery life to perform three tracer tests before having to recharge the battery.

A polypropylene T-piece is used to separate the two electrodes. The centre of the T-piece provides a place where a digital thermometer integrated circuit can be mounted within a protective stainless steel tube.

Since accumulated fouling and minor geometric changes will affect the cell constant, it was decided to eliminate these with a calibration procedure at the beginning of each test.

Temperature compensation

The temperature of the sample may vary during the test as a result of on-off control used for steam injection. Conductivity measurement is very sensitive to the temperature of the solution. The SASTA manual (Anon, 2009) presents a correction for temperature given by:

$$\text{Conductivity at } T_{ref} = \frac{\text{Conductivity at } T}{1 + \alpha(T - T_{ref})}$$

The reference temperature, T_{ref} , needs to be chosen close to the operating temperature. For measurements in a laboratory, the reference temperature commonly used is 20°C. The normal temperature for diffuser tracer measurements, however, is much higher than this and it is advisable to choose a reference temperature closer to the actual operating temperature, T , to reduce the influence of errors in the estimation of the coefficient α .

The value of α for NaCl and KCl is 0.021, but varies for different substances. A slightly higher value of 0.023 is used for conductivity ash in juice (Anon, 2009). Since the tracer used is NaCl, a value of 0.021 is recommended.

Conductivity-concentration relationship

Calibration

A calibration procedure was introduced to:

1. Address problems with variability between conductivity cells.
2. Accommodate changes in surface characteristics of the electrode.
3. Compensate for any non-linear behaviour of the detector over the full range of conductivity measurement.

A sample of juice is extracted from the diffuser at the desired measurement point and the conductivity of the sample is measured with the cell. One gram of salt is added to one litre of the juice sample and the conductivity of the mixture measured again. This gives a two-point calibration in the conductivity range that would be expected during the tracer test. This procedure is repeated for all of the conductivity cells at their various measurement points.

Verification of output

To verify that the output from the equipment was representative of the true tracer concentration, a sample of mixed juice was obtained. The normal calibration process described above was performed using the mixed juice sample at room temperature so that the result reported represented the concentration in grams per litre.

Measurements of relative salt mass added, conductivity and tracer equipment output were obtained by increasing the salt (NaCl) content of the juice sample from 0 to 1 g/L. The measurements were conducted at ambient temperature of 18°C. The conductivity was measured using a WTW inolab Cond Level 1 conductivity meter with a TetraCon® 325 temperature compensated graphite probe. The results of the measurements are shown in Table 1. A linear regression between the conductivity meter result and the weighed salt gives a correlation coefficient (r^2) of 0.9997.

Table 1. Relationship between conductivity and salt concentration.

Added salt concentration (g/L)	Commercial meter ($\mu\text{S}/\text{cm}$)	SMRI tracer equipment (g/L)
0.0	4.48	0.00
0.1	4.60	0.10
0.2	4.71	0.19
0.4	4.98	0.39
0.6	5.24	0.57
1.0	5.75	0.96

The relationship between the tracer equipment and the weighed salt concentration is shown in Figure 3. A high level of correlation was also observed with this relationship. A zero intercept was forced in the regression. It would be expected that there would be a slope of unity. The small difference can be attributed to small errors in the weighing of salt and measuring volume of the juice during the calibration process.

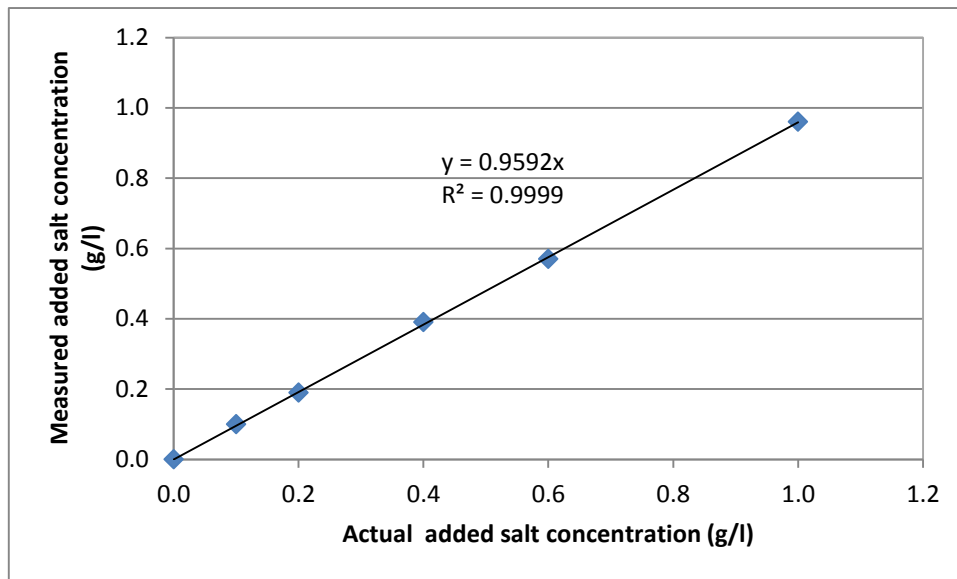


Figure 3. Predicted salt concentration versus actual salt concentration.

Data collection process

Placement of conductivity cells

As the system evolved it was decided to measure the conductivity in five consecutive trays to adequately define the time-conductivity relationship of juice leaving the cane bed. Experience has shown that most of the tracer can be accounted for in five trays. A sample point is required on the pipelines from each of the relevant trays. A small side stream passes out of the main pipe and flows through the conductivity cell.

Apart from the obvious problem of fibre blocking the sample point, placement of the sample point above the level of the sprays may result in a negative pressure and no sample flowing through the cell.

Testing

The system is designed to report tracer concentration directly. To achieve this each of the cells is calibrated using juice extracted from the measurement point. This gives a two-point range from which the concentration can be inferred from the conductivity measurement.

The test is started by measuring the average background conductivities for a few minutes. This gives a baseline from which the additional conductivity from the salt is measured. The 200 L salt solution is then introduced into the spray from where it would be expected that the juice would come out in the direct tray. At the same time the data logging is started. The test continues until all the channels have returned to the baseline conductivity or the first conductivity peak has been fully recorded for each of the channels. The recycle of salt may result in secondary peaks which must be discarded. The average time taken for the salt to percolate through the cane bed is measured relative to the time that the tracer was introduced, so this time needs to be carefully recorded.

Data selection

Start time

The tracer test essentially plots out the impulse response of the system. The time of the impulse needs to be noted. If the recycle stage pump is used for injection, this is conveniently marked by a short burst of high conductivity as can be seen in Figure 4 as the injected sample passes the sample point. In other cases, a manual record of the injection time will be required.

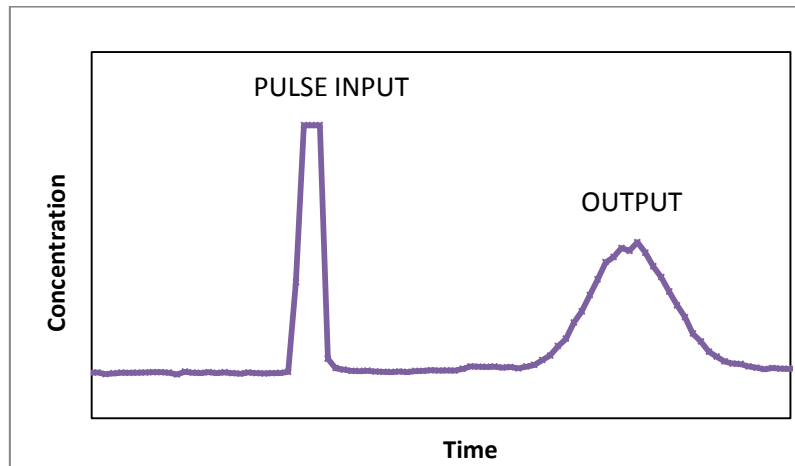


Figure 4. Typical trace of recycle stage.

Base conductivity

The concentration of the salt peak is taken as the difference between the background conductivity and the instantaneous reading scaled to read as salt concentration based on the calibration data. Occasionally, the background conductivity will drift during the test. In this case, a straight line interpolation may be used to compensate for the drift. Although it may be argued that the drift is unlikely to be linear, no other data is available to improve the compensation function.

Conductivity trace

The portion of the curve representing the passage of the tracer needs to be selected. This helps to reduce the effect of background noise on the interpretation of the signal. In some cases, the tracer that is in the recycle stream will return to the direct tray. This results in double peaks. It is important only to consider the first peak.

A sample of the trace that can be expected once the relevant response has been selected and baseline conductivity removed can be seen in Figure 5. The outputs from each channel are summed and presented as the grey area.

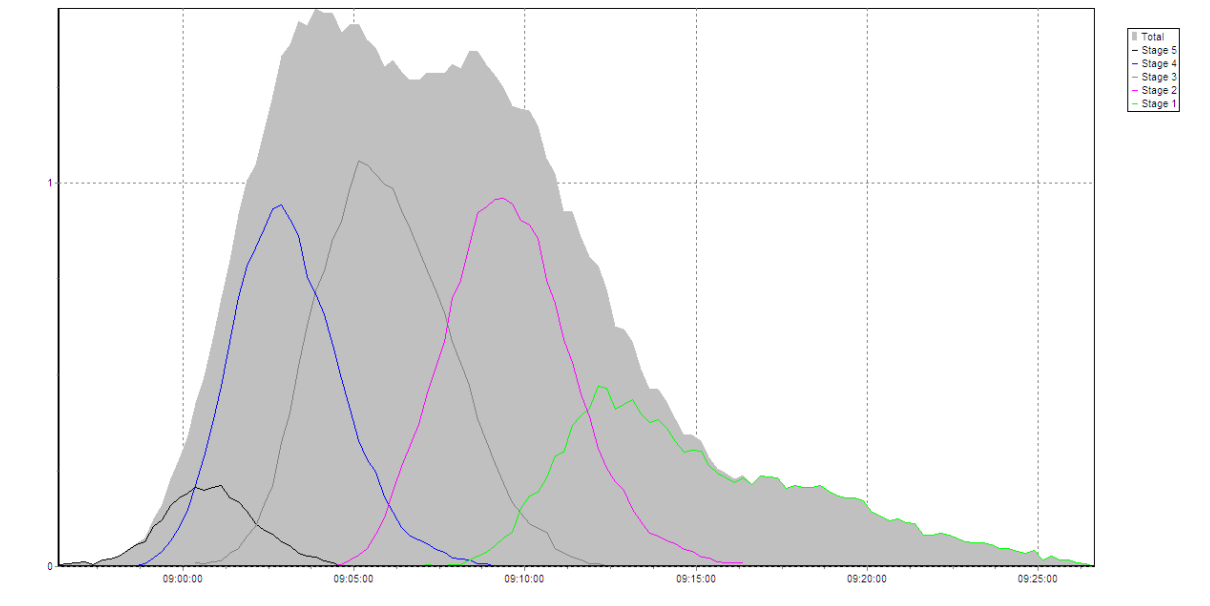


Figure 5. Typical trace for each tray with cumulative trace.

Routine data analysis

Objective

Parameters that can be changed in an existing diffuser are bed depth, bed speed, position of application of juice, imbibition application rate and degree of preparation. While changing of the bed height, bed speed and imbibition rate, and to a lesser extent preparation, can easily be done during operation, these interventions will influence the entire diffuser. Changing the point of application, however, requires mechanical changes to the spray orientation or position but provides a means to compensate for variations in the percolation behaviour of the cane bed along the length of the diffuser.

At the design stage knowledge of the dispersion of the juice and the mean residence time, or mean percolation rate, is needed to choose the stage length and the distance between the spray and the outlet tray. After manufacture it is only the spray position that can be varied to give the desired flow pattern. The tray position is set according to the residence time and the bed speed. The analysis technique needs to estimate the relationship between bed and juice movement. The positioning of the trays can be calculated using the relationships described by Rein and Ingham (1992).

Area moment calculation

Mechanism

A simple analysis method is to calculate the position of the centre of the time-concentration curve. This technique, known as the mean residence time, gives a simple calculation according to the Euler discrete approximation:

$$\bar{t} = \frac{\sum C_i t_i}{\sum C_i}$$

where C_i is the concentration measurement in the i th time interval,
 t_i is the time until that interval.

This may be modified to a higher order integration algorithm if desired.

Sources of error

Sometimes the tracer spreads over more than five trays and some will be missed. Consequently, some of the data is ignored, causing minor errors, when the mean residence time is calculated.

Some variation in the conductivity curve results from inconsistencies within the cane bed. Ideally, some smoothing of the curve would be desirable before attempting to perform the numerical integration required to calculate the mean residence time.

It is assumed that the tracer represents the flow of the juice within the diffuser. The tracer itself represents a high concentration which would disperse according to Fick's law. The concentration gradients of brix in juice would not be as great and so the dispersion effects at the boundary of flow from a particular spray would not be as marked.

If the trays are not kept empty during the test then dilution and mixing will occur, leading to a reduced signal, distortion of the trace and a delayed response.

Curve fitting to model

In the work that was done by Love and Rein (1980) a dispersed plug flow model is suggested. They started with the differential equations and applied a solution. It is possible to derive estimations of percolation velocity and vertical and horizontal dispersion from the curve fit. The technique, however, involves integrating the predicted concentration over the stage. This can be done analytically. The model includes the error function which is determined using an integral which has no analytical solution. The result can be coded on a computer if necessary.

The advantage of this technique is the extra parameters which may be derived from the data, particularly for the design process.

Although the model is reasonably complete, differences between the model and measured data are still evident. The model can only be fitted to available data. Truncated data may result in distortions of the fit. Other errors are related to mathematical and computational approximations which are usually small compared to the experimental variations.

Choice of analysis

The area moment method has the advantage of simplicity. The calculation involves the ratio of two simple summations. This is, however, at the expense of losing dispersion information. This is the method generally chosen by the SMRI for calculating the tray advances necessary to achieve the desired rate of recycle and hence liquid levels in the diffuser cane bed.

The curve fit, on the other hand provides more information. Substantially more complex iterative calculations and numerical integrations are required to solve for these parameters. During the design of the diffuser it is essential to have this information. Consequently, the model fit approach was necessary during the development of the diffuser design philosophy.

Conclusion

Tracer testing is essential for tuning a diffuser to give optimum performance. There are so many variables associated with the performance of a diffuser that an analytical approach is impractical. The percolation characteristics of cane depend on variety, and climatic, seasonal and field conditions.

Sodium chloride has been used as a tracer medium in diffusers for many years. It has the advantage of being low cost and yet is readily detected with conductivity measurements. The methods of conductivity detection have evolved over the years. At the same time, computing power and communication technologies have improved rapidly. Even technologies that were state-of-the-art several years ago are no longer supported.

The SMRI has embraced these changes in technology, combined with the opportunities afforded by new technologies, to simplify the once labour intensive process of performing a tracer test on a diffuser. The system has been successfully used in several tracer tests demonstrating the simplicity of use. Technologies and ideas are continuously improving and may still lead to further developments in the methods of diffuser tracer testing.

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