UNIVERSIDADE DE SAO PAULO
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Análise comparativa de diferentes técnicas de monitoramento do nível líquido em um difusor de cana-de-açúcar

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Comparative analysis of different techniques to monitor liquid level in a cane diffuser bed

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ABSTRACT

SEGURA-ANGEL, D. M. **Comparative analysis of different techniques to monitor liquid level in a cane diffuser bed. 2019**. 133 f. Doctoral (Thesis) – School of Engineering of São Carlos, University of São Paulo, São Carlos, Brazil 2019.

The extraction of sucrose in a sugar cane diffuser depends on the percolation rate of juice through the cane bed. High percolation rates promote mass transfer and increase the wetness of the cane bed (i.e. liquid hold-up within the bed) thereby improving sucrose extraction. However, increasing the rate of juice applied to the surface of the cane bed above the maximum percolation rate results in flooding, causing uncontrolled mixing of juice, destruction of the brix profile and reduced extraction. Therefore, to avoid flooding, the liquid holdup in a stage-wise counter-current diffuser must be monitored and controlled through the automation of the spray position responsible for distributing the liquid onto the bed surface, according to the settings selected.

Currently, the liquid level is controlled by inspecting of a group of sight glasses in the diffusers, this technique requires at least 12 operators working as long as the diffuser is under operation, as a result, this method is unfeasible in practice. In addition this measured is limited by the manual data acquisition and the short sampling time interval.

Most of the conventional methods to measure liquid holdup are not suitable for this application, so new methodologies were introduced such as conductance measurements. Other researchers opted for using manometers to measure the pressure on a laboratory scale. Nevertheless, no satisfactory results were presented and the results from the experiments trials performed in a full scale have not been widely accepted; additionally, no subsequent work has validated or invalidates these results. Therefore, the aim of this study is to test the viability of using a manometers, conductivy meters and impedance meters to assess the observed liquid level in a cane diffuser bed, in order to provide the necessary information to control to adjust the spray position, which can optimise percolation rates.

Electrical impedance has never been measured in a cane diffuser neither on a laboratory scale. Therefore, a new impedance measurement system capable of recording measurements over an adjustable impedance range has been designed and constructed to detect the fluctuations of capacitive and resistive effect in a cane bed.

The results of the experimental trials of conductivity, impedance and pressure conducted on the Tongaat Hulett cane diffuser at the Maidstone factory in South Africa are reliable techniques to indirectly measure the level of the liquid within the cane bed. Reproducibility tests were performed to confirm the results presented in this research.

The results of the test of impedance show that the capacitive effect is not significant and it is not related to the flooding of the cane bed neither with a specific characteristics of the sugarcane or the extraction process. In the same way, the conductance results show that the flow rate and the conductance only have the same fluctuations under special operating conditions such as when the diffuser is being fed and when the recirculation pumps are switched on and off.

The relationships between variables such as conductance, piezometric level, and the liquid level were found through the development of mathematical models. Where the adjustment of the constants of a linear function of permeability permitted to validate the experimental data, in the case of the technique of pressure measurements. On the other hand, the mathematical models were created based on several equations such as second-order transfer equations and Darcy's equations.

Keywords: Conductance, pressure, impedance, observed liquid level, diffuser, sucrose extraction, full-scale test.

RESUMO

SEGURA-ANGEL, D. M. **Análise comparativa de diferentes técnicas de monitoramento do nível líquido em um difusor de cana-de-açúcar. 2019**. 133 f. Tese (Doutorado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, Brasil, 2019.

A extração de sacarose em um difusor de cana-de-açúcar depende da taxa de percolação do liquido pelo leito da cana. Elevadas taxas de percolação promovem a transferência de massa e aumentam a humidade do leito de cana (isto é, retenção de líquido no interior do leito) melhorando assim, a extração da sacarose. No entanto, o aumento da taxa de liquido aplicada à superfície do leito da cana acima da taxa máxima de percolação resulta em inundação, causando mistura descontrolada de suco, destruição do perfil brix e redução da extração. Portanto, para evitar inundações no difusor, o nível do liquido no leito de cana deve ser monitorado e controlado através da automação da posição de spray responsável pela distribuição do líquido na superfície do leito de cana.

Atualmente, o nível do líquido é controlado por inspeção visual nos visores instalados em alguns módulos do difusor. Esta técnica requer de pelo menos 12 operadores trabalhando enquanto o difusor está em operação, como resultado, este método é inviável na prática. Ademais, esta medida está limitada pela coleta manual de dados e pelo tempo de amostragem.

A maioria dos métodos convencionais para medir o nível de líquido não são adequados para esta aplicação, portanto, novas metodologias foram introduzidas, como medidas de condutância entre a superfície do leito de cana e o difusor, e podem ser utilizadas como um indicador do nível do líquido. Outros pesquisadores optaram por usar manômetros para medir a pressão em um difusor experimental no laboratório. No entanto, eles não apresentaram resultados satisfatórios e os resultados dos experimentos realizados em escala industrial não foram amplamente aceitos; além disso, nenhum trabalho subsequente tem validado ou invalidado esses resultados. Portanto, o objetivo desse trabalho é avaliar a viabilidade de usar manômetros, medidores de condutividade e medidores de impedância para avaliar o nível do líquido observado em um leito de cana e assim fornecer as informações necessárias para controlar e ajustar a posição de pulverização, o que pode otimizar as taxas de percolação.

A impedância elétrica nunca foi medida em um difusor de cana nem no laboratório. Por tanto, um novo sistema de medição de impedância capaz de registrar medições em um intervalo de impedância ajustável foi desenhado e construído para detectar as flutuações do efeito capacitivo e resistivo no leito de cana.

Os resultados dos experimentos de condutância, pressão e impedância foram conduzidos no difusor de cana de Tongaat Hulett na fábrica de Maidstone são técnicas confiáveis para medir indiretamente o nível do liquido do leito de cana. Testes de reprodutibilidade foram realizados para confirmar os resultados apresentados nesta pesquisa.

Os resultados dos experimentos de impedância mostraram que o efeito capacitivo não é significativo e não está relacionado com a inundação do leito de cana, nem com nenhuma característica especifica da cana o do processo de extração. Da mesma forma, a análises dos resultados dos testes de condutância mostraram que a vazão e a condutância só têm as mesmas flutuações sob condições especiais de operação tais como quando o difusor está sendo alimentado com cana-de-açúcar e quando as bombas de recirculação são ligadas e desligadas.

A relações entre as variáveis como condutância, pressão, impedância e nível do líquido foram encontradas através do desenvolvimento de modelos matemáticos. Onde, o ajuste das constantes de uma função de permeabilidade lineal permitiu validar os dados experimentais no caso da técnica de medição de pressão. Por outro lado, os modelos matemáticos foram criados baseados em diversas equações como equações de transferência de segunda ordem e a equação de Darcy.

Palavras-Chave: Condutância, pressão, impedância, nível do líquido observado, difusor, extração de sacarose, testes a escala industrial.

LIST OF FIGURES

LISTS OF TABLES

LISTS OF SYMBOLS

α	Confidentiality interval (%)
A_t	Data in the position t which is the current position of the data (dimensionless)
b	Coefficient relate to sugarcane preparation equipment (dimensionless)
C	Crushing capacity (TCH)
C_1	Conductance of the first channel (S)
C_2	Conductance of the second channel (S)
C_3	Conductance of the third channel (S)
C_A	Conductance average of the three channels (S)
D	Roll diameter (m)
e_A	Axial distance between the rolls (m)
F	Total hydraulic load on the pressure roll (ton)
f	Sugarcane fiber (%)
F_r	Flow rate (l/s)
g	Gravitational acceleration (m/s^2)
i	Coefficient filter (dimensionless)
i_p	Current on the test resistors (A)
K	Permeability (m^2)
K_m	Average permeability of the cane bed (m^2)
k_1	Constant (dimensionless)
k_2	Constant (dimensionless)
L	Roll length (m)
m	Massa (kg)
MA	Data filter (dimensionless)
M_1	Position of the manometric tube located at 0.72 m from the screen of the diffuser (m)
M_2	Position of the Manometric tube located at 0.97 m from the screen of the diffuser (m)
M_3	Position of the Manometric tube located at 1.17 m from the screen of the diffuser (m)

M_4 Position of the Manometric tube located at 1.315 m from the screen of the diffuser (m)

MSE Mean square error (dimensionless)

μ Dynamic viscosity (Pa.s)

n Rolls rotation velocity (RPM)

n_p Number of periods to be averaged

η_1 Constant of the permeability functions (dimensionless)

η_2 Constant of the permeability functions (dimensionless)

η_3 Constant of the permeability functions (dimensionless)

N Number of rolls (dimensionless)

O Power (CV)

P_{max} Maximum Pressure (ton/m^2)

p Pressure (Pa)

PR Percolation rate (m^3/m^2/min)

r Super-speed coefficient (dimensionless)

R_c Resistance of the cane bed (ohms)

R_p Test resistor (ohms)

R_{p1} Test resistor of 100 ohms

R_{p2} Test resistor of 9200 ohms

R_{p3} Test resistor of 545 ohms

ρ Density of the liquid (kg/m^3)

SSR Sum of squared residuals (dimensionless)

SSE Sum of squared errors of prediction (dimensionless)

t Time (min)

τ_1 Constant of time (dimensionless)

τ_2 Constant of time (dimensionless)

u Velocity of the liquid (m/s)

V_c Voltage measured on the cane bed (V)

V_d Voltage difference between the initial and final voltage measured on the cane (V)

V_{fin1} Output voltage of the cane bed (V), considering the test resistor R_1

V_{fin2} Output voltage of the cane bed (V) considering the test resistor R_2

V_{fin3} Output voltage of the cane bed (V) considering the test resistor R_3

V_{ini}	Input voltage of the cane bed (V)
V_p	Voltage measured on the test resistors (V)
V_{p1}	Voltage measured on the test resistors R_1 (V)
V_{p2}	Voltage measured on the test resistors R_2 (V)
V_{p3}	Voltage measured on the test resistors R_3 (V)
V_{fin}	Output voltage of the cane bed (V)
ω_0	Natural frequency no damped (Hz)
W	Cane bed height (m) or (dam)
Z	Observed liquid level about some reference level (m) or (dam)
Z_1	Observed liquid level in the first manometer (m), considering its localization
Z_2	Observed liquid level in the second manometer (m), considering its localization
Z_3	Observed liquid level in the third manometer (m), considering its localization
Z_4	Observed liquid level in the fourth manometer (m), considering its localization
Z_{c1}	Impedance on the cane bed (ohms), considering the test resistor R_1
Z_{c2}	Impedance on the cane bed (ohms), considering the test resistor R_2
Z_{c3}	Impedance on the cane bed (ohms), considering the test resistor R_3
ζ	Damping factor

CONTENTS

Chapter 1

Introduction

Sugarcane has been used as feedstock for production of ethanol on a large scale basis in Brazil for over three decades, where most of the sugarcane mills produce sugar, ethanol, and electricity (DIAS *et al*., 2015). The industrial process of ethanol and sugar production begins with cane preparation and juice extraction, which is used in sequence as the principal raw material for the final product.

The objective of the extraction process is to separate the sucrose-containing juice from the remainder of the cane, mainly fibre. Extraction systems usually adopted are mills tandem and/or diffusers (PALACIOS-BERECHE *et al*., 2014). In recent years, the number of diffusers for sucrose extraction has been increasing significantly in Brazil, from 4 to 23 in 2011 (OLIVERIO *et al*., 2013). This increase is due to factors such as higher efficiency, lower energy costs, and lower maintenance and capital costs (FABER, 2013). For example, Van Hengel (1990) observed that the change of the traditional milling systems by diffusers increased the sugar production from 3 to 6 %, at a very reasonable cost.

In this way, improve the extraction process is an important issue, since between 30 and 40 kilograms per ton of sucrose are lost during the extraction of sugarcane juice (ANSELMI, 2003).

This fact has motivated the development of studies on increasing the efficiency of the extraction process through the modification of operational parameters. In this way, the aim of this research is to monitor the level of liquid in the cane bed, which could allow the automation and control of the spray position responsible for spraying the liquid inside cane bed; as well as, to control the cane preparation and rate of water imbibition. Despite of liquid level measurements being important, they have not been carried out extensively on a plant scale because the equipment, such as floating devices, is not suitable for this application; therefore, measurements of pressure, electrical impedance and conductance are proposed as monitoring techniques of liquid level.

Conductivity meters are commonly used in hydroponics, aquaculture, aquaponics, and freshwater systems to monitor the number of nutrients, salts or impurities in the water and to assess chemical diffusivity in transition-metal compounds (LENNARD & LEONARD, 2006). So, the conductance in the cane bed was explored to monitor the variation of liquid level, since conductance measurements have not been performed yet on a plant scale.

Electrical impedance tomography (EIT) has never been investigated or measured in an industrial cane diffuser or at laboratory scale. This technique is based on an analysis of differences in conductance and resistance patterns at varying frequencies. Some of the proposed applications of the EIT technique include monitoring of lung function, detection of skin, breast cancer, location of epileptic (HOLDER, 2014) and imaging of brain activity (CARPENTER, 2019), as well as diagnosing impaired gastric emptying (TROKHANOVA *et al*., 2010; BROWN, 2003). While EIT methods have not yet gained a significant foothold in the medical imaging community (NRC, 1996), it is the only certified alternative as the first step for the detection of breast cancer. EIT has been shown to work well in both geophysical and industrial processes, and is used to monitor mixtures of conductive fluids, and to locate resistivity anomalies on the surface of the earth.

In this way, electrical impedance tomography methods are an interesting approach to this problem due to its simplicity and robustness. However, mathematically, the problem of finding the components of the impedance from measurements of current and potential is a non-linear inverse problem, which requires advanced methods of signal analysis. Therefore, due to the mathematical complexity of signal analysis, a new methodology and equipment to measure the impedance in the cane bed was proposed in this thesis. The experimental test could not performed in the same operating conditions and using cane from the same harvest, therefore, this was one of the limitations of this work to get more conclusive results.

Additionally, the characteristics of the sugarcane and the fluid-dynamic behaviour of the percolating liquid were described when the recirculation pumps were turned off and when the bed of cane was flooded. Finally, mathematical models were developed to explain the variability of the conductance, of the piezometric head, and of the impedance at constant or varying flow conditions.

1.1 Objectives

The main aim of this research is to study and evaluate the use of different techniques to measure the liquid level within the cane bed and thus to provide the necessary information to the electrical and control department of the mill so they can control and adjust the spray position keeping the percolation rate optimized and increasing extraction efficiency. The spray position is responsible for spraying the liquid on the surface of the cane bed, and the specific objectives are:

- Measure the variation of impedance, conductance and pressure through the cane bed in an industrial diffuser to compare them with the variations of the observed liquid level
- Develop mathematical models to compare theoretical and experimental results and, in this way, understand the physical meaning of the variables and constants of these equations
- Perform computer simulations that allow modification of the initial conditions, to determine the relationships between the different variables such as pressure, permeability, flow rate, conductance and impedance
- Test the effect of different permeability profiles on cane bed pressure variation in the mathematical model
- Design and build an equipment to measure the impedance, considering the technical characteristics of the diffuser
- Conduct experiments that determine how the variation of the operating conditions modify the main variables (flow rate, conductance pressure, and impedance)

This thesis is organized as follows:

Chapter 1: Introduction, problematic, objectives and context of the thesis.

Chapter 2: Bibliographic review of the studies related to cane characteristics and analysis of different sources of information on the research developed in the main extraction systems: diffusers and tandem mills.

Chapter 3: Description of the conductance experiments carried out on a plant scale.

Chapter 4: Tests performed of piezometric head on a plant scale to monitor the liquid level. The construction of a mathematical model allowed to compare the theoretical data with the experimental results.

Chapter 5: Performance of electrical impedance tests on a laboratory scale to determine the existence of a capacitive effect in the cane bed. Due to the mathematical complexity of the problem, we opted to apply an electrical signal as a unit step signal in the tests carried out on a plant scale. Thus, we develop a mathematical modelling that helps to describe the capacitive, and the resistive effect in the cane bed and compares the experimental data with the theoretical data.

Chapter 6: Comparative analysis between the results and methods used to monitor the liquid level, conclusions, and suggestions for future work.

Chapter 2

Review of previous work

A literature review of previous works on the main characteristics of sucrose extraction systems was carried out; Diffusers and mills tandem. A comparative review of these systems is presented and the recommended use for each extraction system, operational data, and the ratio of investment and costs between the mills tandem and the diffusers are described. The study of the characteristics and technological development of mill tandem is important because this is the main extraction system in Brazil.

The historical and technological development of the mills and diffusers was reviewed thus the main components and the operational function of these technologies was described.

2.1 Sugarcane

Extraction of sugarcane juice began in the first half of the 16th century in the Brazilian territory with the purpose of supplying sugar to European countries and, at the time, for the incipient domestic market. The expedition of Martin Afonso de Souza, in 1532, started cane cultivation and implemented the first sugar mill in the state of São Paulo: the Engenho Eramos (a small mill producing sugar and rum), in São Vicente. After that pioneer unit and to reduce transport costs, sugar was produced in states closer to Europe, in the current states of Pernambuco, Bahia and Rio Janeiro. In this initial stage, the mills installed in São Paulo and Rio de Janeiro states already showed the ability to make the sugar industry a profitable activity (OLIVERIO *et al*., 2013).

In the initial period of ProAlcohol (mid 70ties) the crushing capacity was increased without great technological advances, but in the second half of the 1980s, the juice extraction capacity was increased due to the technological improvements in processing equipment and the introduction of new and more resistant cane varieties (OLIVERIO *et al*., 2013).

The introduction of the mechanized cane harvest in 2006 brought about several problems related to the high content of plant and mineral impurities and their processing. Therefore, a new learning process has begun to handle the new raw material and obtain a high economic performance.

Sugarcane is a species of plant belonging to the family of the *Poaceae*, where the juice is used to produce ethanol or sugar and the fibres can be used as fuel for the boilers. Where, the technical potential for energy generation in 2023, with raw materials such as bagasse and sugar cane straw, is 19.5 GW (EPE, 2015)

Sugarcane species are characterized by their genetic variability, environmental factors that influence the amount of vegetable mass and determine the contents of the various components of sugarcane.

Commercial varieties - interspecific hybrids - present a gradual loss of productivity after their maturation, their production life being limited, therefore, they must be replaced by new genetically modified varieties of sugarcane, such as energy cane, which is able to withstand environmental adversities, since the water requirements are few and can be planted in degraded areas. In addition, this is resistant to diseases, pests and environmental modifications produced by the expansion of the culture and the implantation of new technologies.

Products such as paper and dog food can be obtained from the bagasse after going through the hydrolysis process (HORII, 2004). The processing of it can also produce fertilizers, unicellular proteins, organic substrates for many crops and construction materials.

In the case of a sugar-alcohol production, sucrose extraction and energy consumption vary indirectly with the imbibition rate and particle size distribution. Where particle diameter depends on the cane preparation. Therefore, adequate preparation and handling of sugarcane are required to make efficient use of the numerous industrial applications.

2.1.1 Sugarcane characterization

Gascho (1983) describes the phenology of sugarcane from its growth until maturation as:

- Budding: The bud arises simultaneously with the roots of the heel and after three weeks begins the rooting and the appearance of the leaves. The emergence of the shoot takes place 20 to 30 days after cultivation.
- Stem emission: It is the process of emission of the stem (tiller) where the hormones regulate their growth. The harvest is carried out after the formation of the sugarcane bush. When the total cover of the soil occurs with the foliage of the plants, this stage ends.
- Growing phase: The stems grow due to the stimulation of light, moisture, and heat. These accumulate sugar in the heel and can grow up more than three meters in height. Subsequently, vigorous root growth begins, where most of the roots are in the 40 centimetres deep.
- Tiller ripening: these ripen when clumps grow to a height equal to or greater than two meters. Subsequently, when the leaves are yellow and dry, the sugar begins to settle at the median height of the plant. The maximum storage only begins between autumn and winter at low temperatures and in the presence of rain.

As mentioned, cane quality and sucrose deposition depend on factors such as spacing, variety, age, cut, maturation stage, harvesting season, climate throughout the cycle, soil, fertility, irrigation (water or vinasse), cultural treatment, cultivar sanity, and flowering (HORII, 2004).

2.1.2 Processing and cane preparation

The processing of sugarcane begins with the harvest of sugarcane, which is transported to the sugar mill, where it is analysed and weighed. The cane is discharged through hydraulic wires on feeder conveyors. These can be simple or composite with a conventional inclination angle (10 ° to 20 °) or high inclination angle (30 ° to 40 °). Greater inclinations increase the efficiency of washing and allow a greater control of the transporters (D'AVILA, 2008). The cane bed moves from bottom to top by chains during this process.

To remove the impurities from the cane it is washed with water or dry cleaned with the use of ventilators, vibratory separator, conveyors, minerals and vegetable impurities. The dry cleaning of the cane eliminates the use of water and equipment such as decantation tanks, pipelines, pumping stations, and water treatment. In addition, it increases the operational efficiency of the boiler grates and the mud filter, thus, the straw is better used for the generation of electric energy (SORRILA *et al*., 2008). Since, the bagasse contains less amount of sand and mud.

The cane is transported by a metal conveyor to the preparation area, where a set of levelling knives cut the cane and increase the density of the cane bed. Subsequently, the cane is compacted with a shredder, then the cane passes through a rotor with a set of oscillating hammers that rotate in the opposite direction to the conveyor by forcing the cane through an opening of approximately 1 cm along a perforated plate. The cane is shredded to be transported to the extraction system used by the mill.

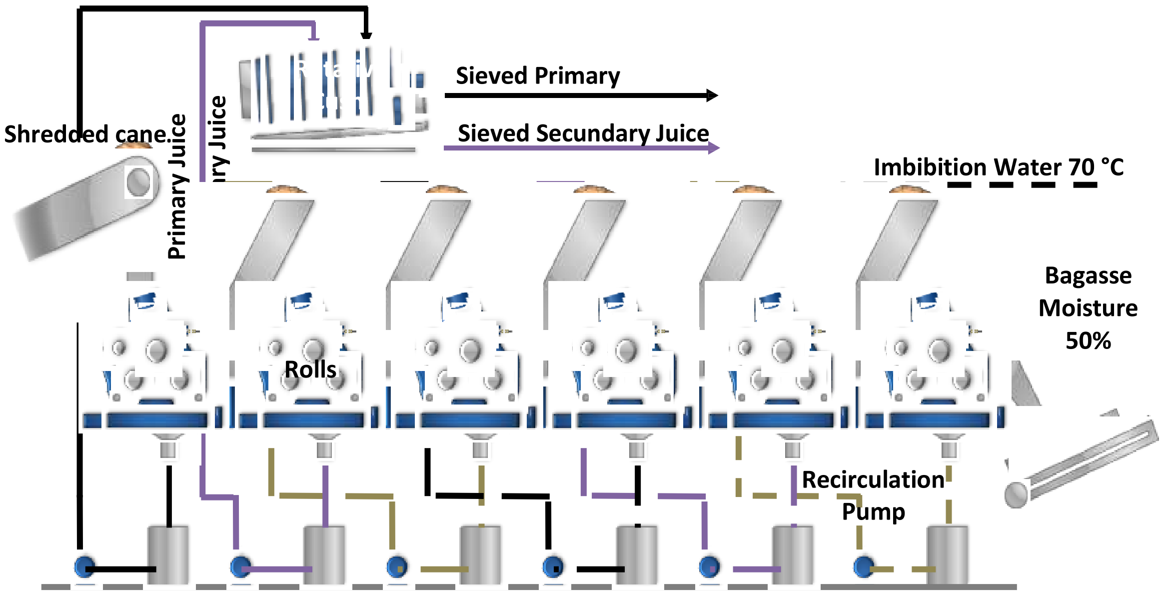
2.2 Mill tandem characterization

The first mills had a design based on family farming activities. For centuries, sugar mills have evolved: initially, juice extraction was achieved by low-efficiency and low-capacity mills driven by animal traction and / or hydraulic wheels; later by steam engines; and, finally, they were driven mainly by steam turbines. (UNIÃO DA INDÚSTRIA DA CANA-DE-AÇÚCAR, 2012). This structure remained until 1975 when the Brazilian government launched the ProAlcohol Program (OLIVERIO *et al*., 2013).

The extraction of sucrose can be affected due to the poor cleaning or sanitising of mill tandems, which result in sucrose losses (HUGOT, 1986). Sucrose destruction can be by acid inversion, enzymatic inversion or microbial infection (REIN, 2007). Acid inversion is when sucrose is chemically converted to its sub-units, fructose, and glucose, mainly under acidic conditions and higher temperatures (REIN, 2007). Enzymatic destruction occurs when the enzyme invertase, found naturally in cane or produced by *Saccharomyces* sp., converts sucrose to its sub-units. Microbial infection occurs under wet and warm conditions. Microbes like *Leuconostoc* sp. can often reduce sucrose to other products like dextrans and organic acids (LIONNET, 1996).

The mill tandem is composed of 4 to 6 mills and every mill is composed by bearing cap, heads, rolls, trash plate and bases as shown in Figure 2.1. The first mill is responsible for 70% of the extraction of the juice contained in the cane.

Figure 3.1 Mill tandem compose for six mills



Source: Oliverio *et al*. (2013)

2.2.1 Historic develop of Mill Tandem

The combined arrangement of a series of mills forms the so-called "milling tandem". Between the years 1970 and 1980 the efficiency of the mill tandem was increased by inserting the chute of Donnelly, the top roll and defibrillator. Each mill had three rollers, mainly Fulton, these were installed in relation to the other roll by chocks and wedges and their position in the bearing cap was determined at the beginning of the harvest.

The bagasse layer determines the pressure and can increase or decrease when the processing rate varies. The efficiency of the extraction process is affected by the infiltration of strange and resistant elements which can damage the bearing (HUGOT, 1986).

2.2.2 Crushing capacity

The crushing capacity depends directly on factors such as: cane fibre (f), relative coefficient of cane preparation equipment (b) as shown Table 2.1, rotation velocity of the milling roll (n), roll diameter (D), roll length(L), number of rolls (N) and indirectly non-measurable factors such as cane quality and feed roll characteristics.

Table 3.1 Relative coefficient of cane preparation equipment

Equipment for the sugar cane preparation	Preparation coefficient (*b*)
1 Knife	1.1 to 1.20
2 Knives	1.15 a 1.25
1 Knife, followed by a Shredder (Searby Model)	1.25
1 Knife, followed by a Shredder (Maxwell Model)	1.22

Source: Hugot (1986)

The crushing capacity (*C*) is determined by the Equation 2.1 (HUGOT, 1986)

$$C = 0{,}8 \cdot \left(\frac{b \cdot n \cdot (1 - 0{,}006 \cdot n \cdot D) \cdot L \cdot D^2 \cdot \sqrt{N}}{f}\right) \quad (3.1)$$

Where D is roll diameter (m); *n* is roll rotation velocity (RPM); L: Roll Length (m); *f* Sugarcane fibre (%); *b* is a coefficient related to sugarcane preparation equipment (dimensionless); N is the number of rolls and C is the crushing capacity (TCH – ton of cane per hour).

2.2.3 Imbibition Process

Imbibition is the process in which water or a mix between juice and water is sprayed onto the surface of the cane bed, in the form of pressurized jets. The purpose of imbibition is to increase the dilution of the juice contained in the sugarcane and simultaneously increase the extraction of the juice in the previous mills.

There are two types of imbibition: simple or compound. Simple imbibition consists of spraying the liquid at each mill from the second mill. In the compound, imbibition water is added to the bagasse going to the last mill. The juice from the last mill is added to the bagasse coming to the penultimate mill and the juice from the penultimate mill is sent to the preceding mill and so on depending upon the number of mills, this is also known as double, triple, quadruple compound imbibition and so on.

The cane juice extracted in the first mill or in the first stage is called primary juice, afterwards, it is strained, where it is separated from the bagacillo and sent separately from the primary juice to be processed. The bagacillo return to the first mill or the first stage.

There are several methods for applying water to the surface of the cane bed. The water is applied by a nozzle, in this case, there is the inconvenience of soaking the top of the layer of bagasse leaving the bottomless soaked. It can also be applied with the pressurization method, so the water penetrates the layer due to the pressure of the jets, causing agitation of the bagasse in the mill outlet, which leads to a more regular and efficient imbibition. In the case of the application of the juice is normally done through nozzles that have the function to distribute it uniformly throughout the whole width of the conveyor.

The advantages of hot imbibition (60° to 80°) are the dilution of the residual juice contained in the bagasse and the increase in temperature in the final bagasse, which can lead to a small decrease in the moisture of the bagasse. However, there are also disadvantages such as the increase in the difficulty of feeding the mills and the application of welds in the mills due to the working conditions of the welders.

The most used process for cane preparation consists of a simple imbibition with cold water and the cutting of the cane which is carried out with two sets of knives triggered by a turbine. Subsequently, the cane is stored and fed to a conveyor. (BRUNELLI; AGUIAR, 2008).

2.2.4 Mill tandem setting

Mill setting determines the most favourable relative positions of the three axes and the bagasse in order to achieve the best feeding conditions and a greater sucrose extraction (HUGOT, 1986).

2.2.5 Mill components

The mills are composed of three rolls or four rolls, as shown in Figure 2.2. Some mills can have a drive motor for the three rollers using an impeller for torque transmission from the upper roller. Other mills use a motor for each roller.

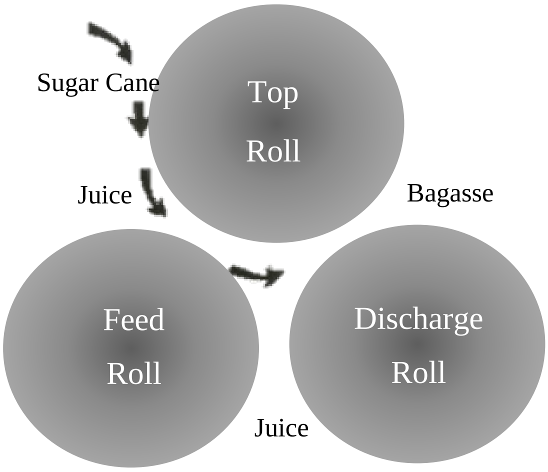


Figure 3.2 Mill tandem rolls

Source: Elaborated by the author

Top Roll

The top roll oscillates to keep constant pressure on the cane bed, even when the feed of cane is not constant, thus prevents an overload. It resists the greatest charge in the mill (hydraulic charge, torque) consume almost half of the total torque of the mill and is subject to flexion against the reactive forces of the feed roll, the trash plate, and the discharge roll. The force is transmitted from the top roll to the other rolls thought to the impeller.

Feed roll

It provides the force to begin the crushing of the cane. The feed roll bearings are adjusted horizontally by a regulating device of the input side headstocks.

Discharge roll

The discharge roll directs the resulting bagasse to the outlet. The bearings of both the feed roll and the discharge roll are made up of a box manufactured in cast steel, a lid manufactured in cast iron and a semi- cast steel.

Trash Plate

The trash plate is manufactured with cast steel and its function is to drive the bagasse from the feed roll to the discharge roll, increasing the mill performance. To achieve this, it needs to intercept the bagasse while still under some compression and transfer it with the least possible loss of compression but minimum friction into the discharge opening. The performance of the extraction and the geometry of the milling depend on the position of the trash plate to be regulated.

Headstocks

The purpose of the mill headstocks is to maintain the mill components (particularly the rolls) in their desired orientation. This orientation needs to be flexible to allow different roll sizes and settings.

The headstocks differ by their location, they are manufactured with cast steel and fixed to the bearing caps by screws. The headers assist the assembly of the fed rolls, make stability to the bearing cap and allow the adjustment of the discharge rolls.

Bearing cap

They are designed to withstand the loads in the mill process and their dimensions establish a great gap between the rolls for a maximum extraction in the grinding. They are manufactured in cast steel and the parts that are exposed to the sugarcane juice are covered with stainless steel. The bearing cap have three gaps, where the three rolls are installed, two laterals positioned on the same plane and one on the top with an inclination of 15°, it is also fixed the hydraulic headstocks at the top.

Chute Donelly

Although this equipment was developed in Australia, it is widely used in Brazil to improve the performance of the feeding of the mills, especially when using a high imbibition rate. In addition, the chute is used to regularize and standardize the process of milling. It also makes the pressure of the rolls on the cane more constant since the chute kept full. A high-speed belt conveyor is used to get a thin cane bed layer since the aperture of the feed chute is little.

When the chute Donelly is used in the first mill a high-speed conveyor belt (100 m/min) and a cane spreader for obtaining a low bed height of cane is required.

Pressure calculation in the mills

A maximum hydraulic pressure value of 1000 to 1100 ton/m^2 is admitted in the mill tandem. This maximum pressure depends on the hydraulic load, the roll diameter, the roll length and the distance between the rolls (HUGOT, 1986).

$$F = \frac{L\sqrt{D \cdot e_A}P_{max}}{3} \quad \textbf{(3.2)}$$

Where F is total Hydraulic load on the pressure roll (ton); P_{max} is maximum pressure (ton/m^2) in the axial plane, disregarding the reabsorption; F is total Hydraulic load on the pressure roll (ton); e_A is axial distance between the rolls (m); D is roll diameter (m) and L is roll length (m).

Power requirements

The power requirements of a sugar cane mill are represented according to the mathematical and empirical expressions established by Hugot (1986). The total power consumed by the first mill is described by Equation 2.3.

$$O = \mathrm{n} \times \mathrm{D}\left\{\mathrm{F}\left[0{,}4\,\frac{6r-5}{\sqrt{r}\left(1+\sqrt{r-1}\right)}\sqrt{\frac{e_A}{D}}+0{,}075\right]+4\mathrm{L}\right\} \quad (3.3)$$

Where *O* is power (CV); F is total Hydraulic load on the pressure roll (ton); D is roll diameter (m); *n* is roll rotation velocity (RPM); L is roll length (m); e_A is axial distance between the rolls (m) and *r* is Super-speed coefficient is the ratio between the average speed in the outlet distance and the peripheral speed of the rolls cover, typical *r* values vary between 1 and 2.

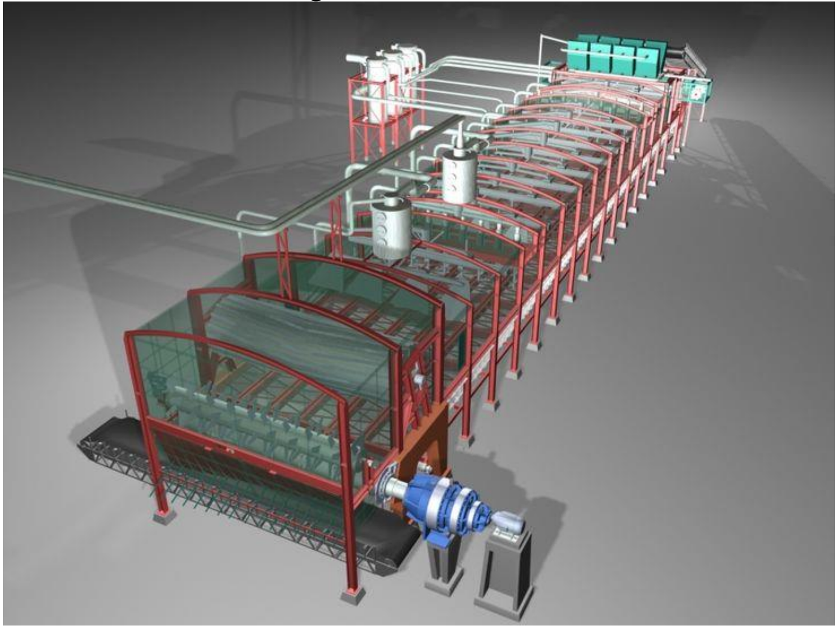
2.3 Diffuser

Diffusers utilise two sucrose extraction processes from prepared cane, namely (a) washing sucrose is mechanically removed from the surface of the fibre using water and (b) diffusion sucrose is transferred from the fibre cells (higher sucrose concentration) to the surrounding (lower sucrose concentration) extract (REIN, 2007). Where the mean percolation is 1.5 m^3/m^2/min and the mean liquid level is 1.5 m

One of the disadvantages of diffusion is the extraction of impurities especially acetic acid which causes major corrosion damage to diffuser roofs, steam pipes, condensate pipes, evaporator and pan domes (SCHÄFFLER *et al*., 1988).

Bagasse diffusers were installed prior to sugarcane diffusers, where the cane processed by a mill and subsequently feed the diffuser. The first bagasse diffuser was installed in South Africa in the 1960s, and 25 years later the first cane diffuser, Galo Bravo, was installed in São Paulo, Brazil. The diffuser is composed of a set of stages between 10 to 18 stages as shown in Figure 2.3, and the number of stages depends on the crushing capacity. Afterwards, cane diffusers became popular in South Africa, Swaziland and Zimbabwe. The spreading of this technology in other cane-producing areas of the world has been much slower.

Figure 3.3 Cane diffuser



Source: Diffuser designed by Sugar technology international

Initially, the bagasse diffuser presented some problems related to high moisture levels and impurities of the bagasse, making it difficult to burn in boilers. This problem occurred due to the fact that those units were imported and projected for sugar beet factories. Another important issue is the cane preparation since initially the operators did not know that preparation of at least 90 - 94 preparation index (PI) is required to achieve an extraction of more than 97% in a diffuser (LOUBSER; GOOCH, 2004; PAYNE, 1968).

On the other hand, technological advances since 1984 have not been significant until Bosch Projects introduced the 'Chainless Diffuser' concept in 2006.

The extraction process begins with the cane preparation which is carried out with hammers and sets of knives triggered by a turbine, Subsequently, the cane is fed to a conveyor to the diffuser, where the application of imbibition water in the cane for the extraction of the juice through a lixiviation process. The water and the juice re-circulated in the equipment are heated with pressure saturated steam.

2.3.1 Cane Preparation

The cane preparation is the process of breaking the structure of the cane to facilitate sucrose extraction. Cane preparation is controlled according to fluid retention in the diffuser bed, thus the maximum contact time between the solid and liquid fractions is very important for extraction.

As mentioned above, cane preparation is one of the most important factors of the extraction process, as well as the way in which the cane is prepared since long fibres are preferred because it results in a stable cane bed and open enough to allow high percolation rates, mass transfer, which increases sucrose content in the juice.

It is achieved in heavy duty shredders with a minimum of knifing since intensive knifing reduces the average fibre length. Where the shredder should be set to run at a steady speed to give steady feed into the diffuser. However, the finer cane preparation can cause flooding so the cane preparation must be finely controlled.

Regarding cane preparation, the Cosecana (Association of the producers of sugar cane, sugar and ethanol of the state of São Paulo), standard 40 says: "The disintegrated material should contain only small and homogeneous particles, without pieces or splinters, and that it provides a preparation index (PI) of 90%. In time, a tolerance of ± 2 percentage points shall be allowed". The index of preparation is determined based on the Manual of Cosecana of 2006, as presented in Appendix A.

The measurement of the degree of cane preparation is a difficult task and existing techniques are not always reliable. The most common measure is the Preparation Index (PI), which assesses the degree of preparation by measuring how much of the sugar in cane is easily washed out of the prepared cane sample. However, it is not a reproducible measurement since it is affected by cane variety and the amount of extraneous matter in cane.

2.3.2 Imbibition

In the diffuser the process of imbibition is carried out in counter-current, where an optimum imbibition corresponds to 300% on fibre. Compound imbibition (see section. 2.2.3) is frequently used in a cane diffuser.

2.3.3 Types of diffuser

Different kinds of diffusers were patented and designed, however, the cost of development of diffusers has proved to be too high for most manufacturers and only about six models are now in commercial operation. The diffusers are categorised as follows according to Lamusse (1980).

2.3.3.1 Horizontal bed diffuser

These diffusers are composed of stages where the cane bed moves on a thick mat and the imbibition is carried out counter currently from the last stage of the cane diffuser. The cane bed is about 50 - 60 m long and ~1.5 m height. Juice recirculation is accomplished by a series of pumps and sprays. They are rectangular in shape as shown in Figure 2.4 and their designs have about the same overall dimensions for a given capacity. The rectangular diffusers are the most widely used diffusers in industrial operations now.

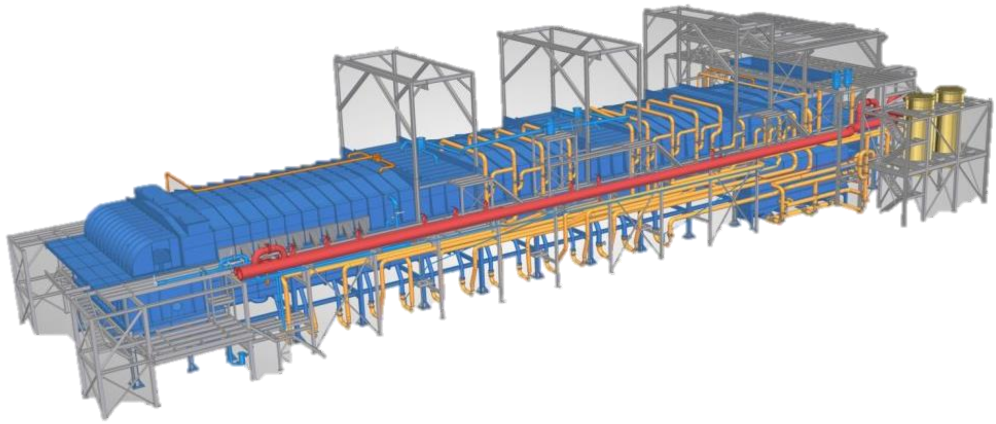


Figure 3.4 De Smet diffuser

Source: De Smet (2019)

The best-known diffusers of this type are BMA, De Smet, Silver Ring, Burnett, and Huletts. The BMA and Huletts diffusers differ from the De Smet and Silver Ring in having a fixed screen, with a series of chains which transport the cane bed across the screen. This generally results in a cheaper diffuser for the same screen area. In addition, BMA diffuser has a drag type conveyor whereas De Smet diffuser uses an apron type conveyor made up of screen sections.

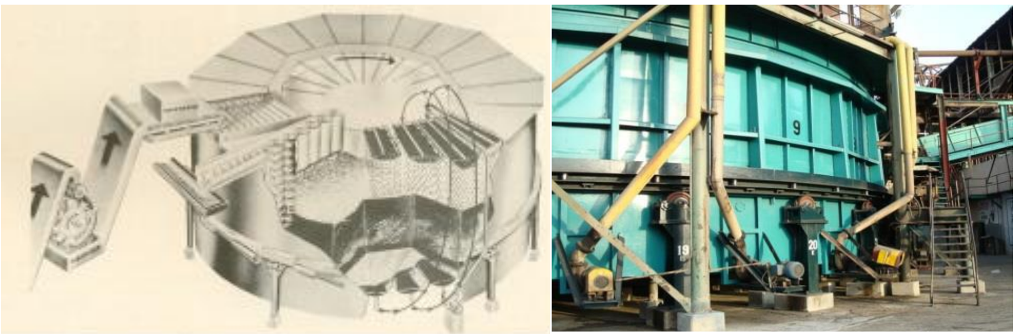
An issue of the rectangular bed diffusers is the overflow of juice from the bagasse discharge end when the percolation rate is low.

Another type of horizontal diffusers are circular diffusers such as the silver ring diffuser and the Rotocell. The Silver Ring consists of an annular trough with a screen bottom which is filled with prepared cane or bagasse to a depth of about 1.5 meters. Rotation of the trough by hydraulic rams brings the bed under a series of sprays through which juice is pumped counter current to the bed. Discharge of bagasse from the trough at the end of the diffusion cycle is by means of vertical screws or by an elevator conveyor.

The operation of this diffuser permits controls of the flooding since the walls and bottom form an annular tank. The circular geometry increases in screen area to handle larger throughputs.

The Rotocell (Figure 2.5) has the same shape as the Silver Ring but is divided into compartments by vertical baffles at the end of the diffusion cycle, the bottom screen of each cell swings open and dumps the bagasse. This solution obviates bagasse discharge difficulties which have been reported with the Silver Ring.

Figure 3.5. Circular diffuser (Silver Ring)



Source: Faber (2013)

The acceptation of the circular diffusers have been limited to Latin America and the pacific with few units in operation (LAMUSSE, 1980).

2.3.3.2 U-Shape diffuser or True counter-current diffusers

The U-shape diffuser is a beet diffuser and the only diffuser of this type which has operated industrially is the DDs (Danish Sugar Company; De danske SukkerEabrikker). It has been built for relatively small throughputs and this, coupled with the fact that it has always been sold as a bagasse diffuser, may be the reason why it has not been more widely accepted in the cane industry.

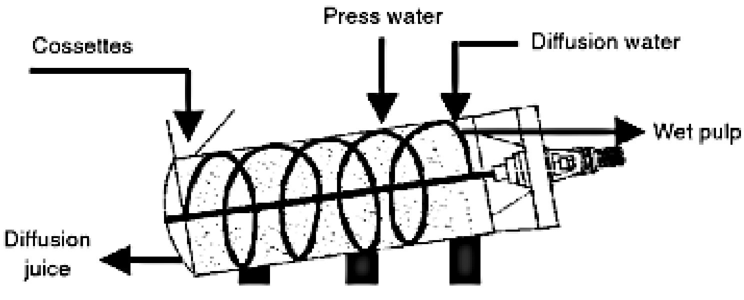


Figure 3.6 Diagram of Silver-DDs diffuser

Source: Asadi (2007)

The DDS diffuser consists of an inclined trough with a semi-elliptical cross-section as shown in Figure 2.6. Two counter-rotating horizontal scrolls in the trough move the bagasse forward. The scrolls are geared to provide alternate squeezing and decompression of the bagasse. Counter-current juice recirculation is by gravity and is promoted by the slope of the diffuser which is inclined towards the bagasse discharge end. The DDS is characterised by the fact that it operates in a flooded condition. It is often referred to as a "submerged" type diffuser (ASADI, 2007)

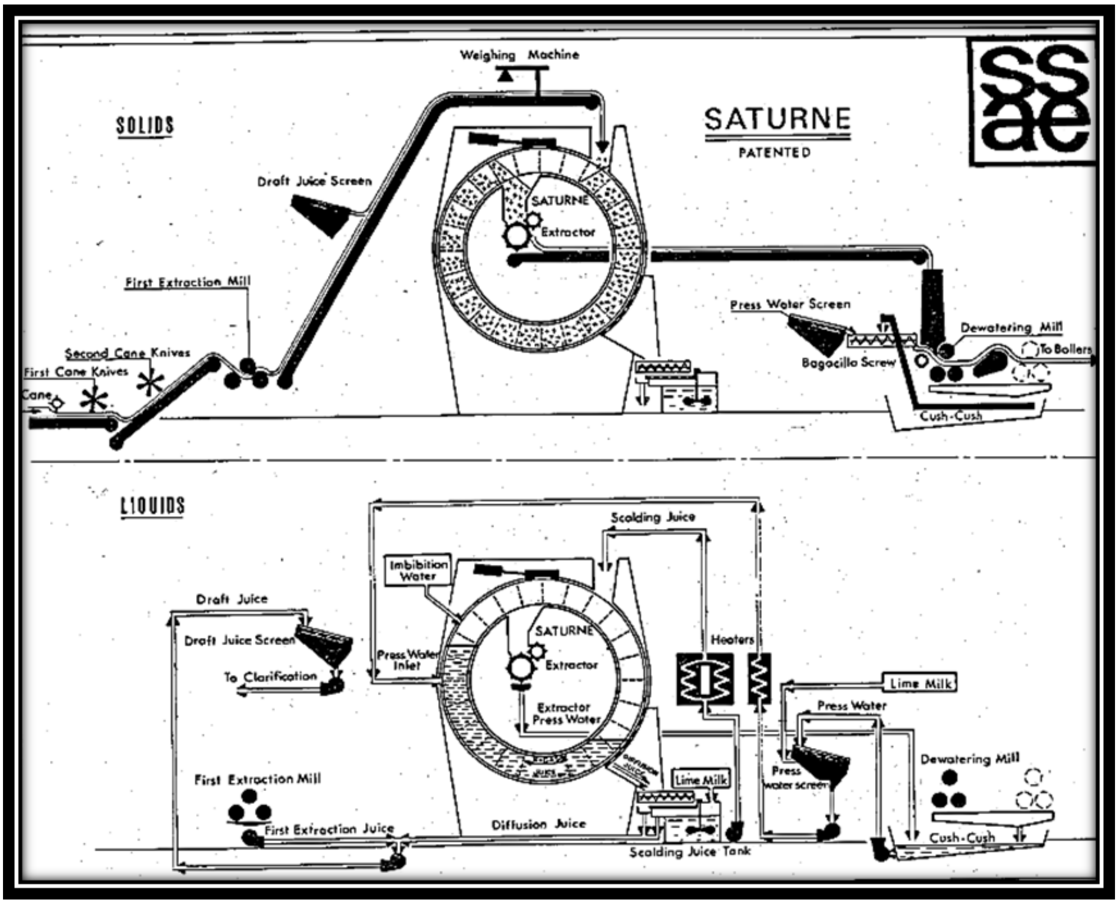
2.3.3.3 The vertical annular diffuser

The Saturne diffuser consists of a vertical annular ring divided into compartments by radial grids as shown in Figure 2.7. The Saturne diffuser is characterized because bagasse travels counter-current to the juice and is immersed in the juice for most of its path, while juice is forced through the bagasse mat by gravity.

The grids rotate slowly like the impellers of a giant centrifugal pump and convey the bagasse from the feed point situated at about 2 o'clock on the ring to the discharge at 10 o'clock. Discharge is through an opening in the inner annulus of the ring.

The general concept of the Saturne is extremely simple. This diffuser has no circulation pumps, no scrolls, screws, shafts or chains and is therefore very low on maintenance costs. It is driven by a hydraulic ram which pushes tangentially on the ring and rotates it on the rolls on which it is suspended.

Figure 3.7 Schematic flow diagram of solids and liquids through Saturne diffuser



Source: Barre (1971)

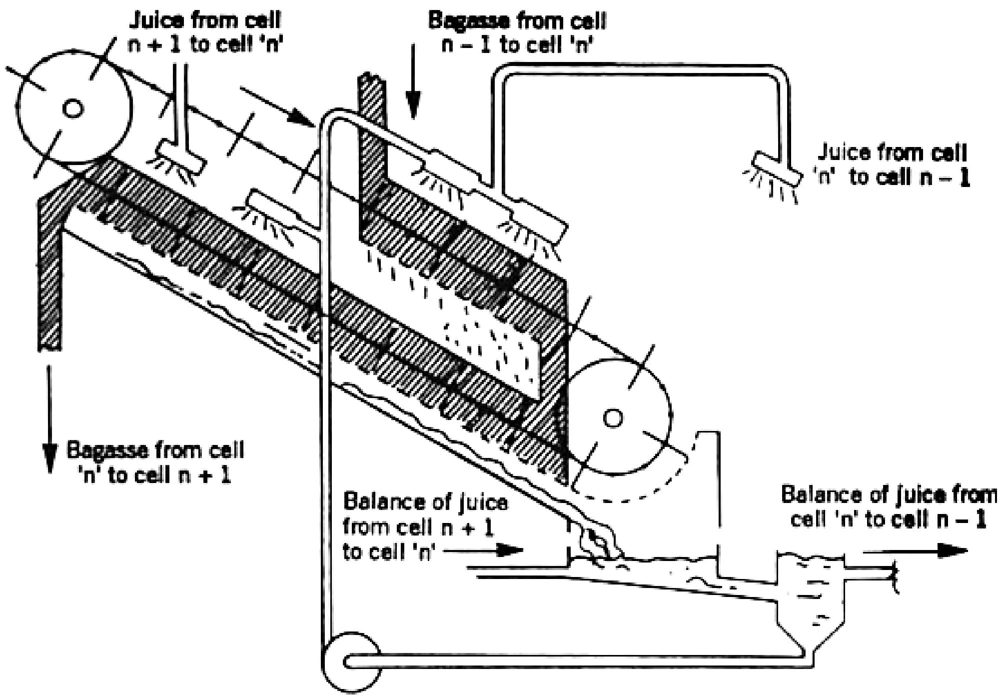
The very small floor space required by the Saturne is an advantage for installation in existing factories. The height to which bagasse has to be elevated can present conveyor layout problems. The Saturne does not escape the limitations on capacity increase brought about by its circular shape. About five diffusers of this type have been built as bagasse diffusers with capacities ranging from 80 to about 150 tons of cane per hour. They have been installed in Spain, India, Mauritius, and West Africa.

2.3.3.4 The inclined bed diffuser

There are two Van Hengel diffusers in operation, one in South Africa and the other in the Philippines. It is characterized by to tumble the bagasse bed at frequent intervals in order to prevent compaction and to improve percolation and by to build the diffuser into a number of relatively small units which can be added together to provide the required capacity.

The long horizontal conveyor typical of rectangular diffusers has been broken up into a series of relatively short conveyors inclined at an angle of about 30 degrees as shown in Figure 2.8.

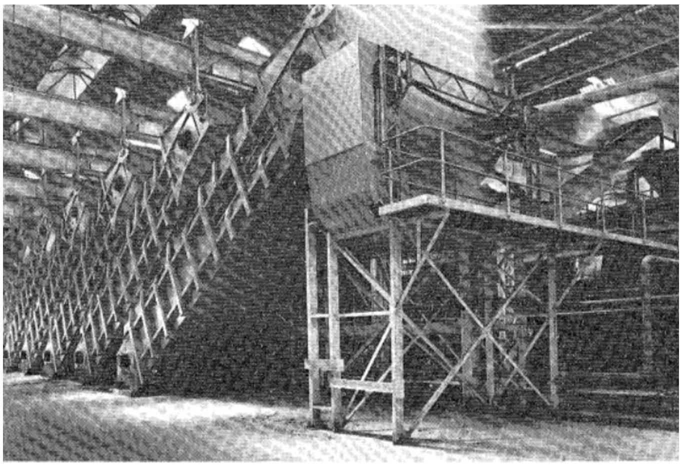
Figure 3.8 Schematic diagram of diffuser stage



Source: Baikow (1982)

The mat of fibre on the conveyors is much thinner than in horizontal bed diffusers and is tumbled as it falls from one conveyor to the next. In the F & S diffuser extraction takes place by percolation of the juice through the bagasse on the conveyors and also by mixing of the juice and bagasse in the boots at the lower end of each conveyor (BAIKOW, 1982). Control the flooding is easier than in rectangular diffusers because of the inclination of the conveyors which limits any overflows to a single stage as shown in Figure 2.9.

Figure 3.9 F & S bagasse diffusers, Pongola, South Africa



Source: Lamusse (1980)

2.3.3.5 Comparison between the main types of diffuser

A comparison of the moving screen and fixed screen diffusers leads to the following considerations according to Rein (1995):

- The moving screen diffuser requires double the screen area, as half the screen is inoperative on the return strand.
- Fixed screen diffusers have a heavy press roll riding on the cane which leads to a lower moisture content of diffuser discharge bagasse.

- Because of reduced friction, the drive power required on a moving screen diffuser is generally lower, typically 30 kW for a 300 ton/h diffuser compared to 100 kW for a fixed screen diffuser. However, most of the power used by diffusers is on stage juice pumps.
- Because moving screen diffusers cannot seal the top surface with a heavy press roll, discharge of cane from moving screen diffusers is by lifting screws (Silver Ring) or lifting drum (De Smet). Discharge from fixed screen diffusers is simpler, by gravity with a kicker to smooth out the flow.
- Perhaps because of the difficulty of sealing between the moving screen and the stationary side walls, moving screen diffusers lead to higher levels of suspended solids in juice (typically 0.6% compared with 0.1% on diffuser juice), the requiring draft juice screens and a press water clarifier.

In general then it can be said that the horizontal moving bed type diffuser has captured the cane diffusion market to the exclusion of other types of diffuser, due to their relatively low cost, simplicity of operation and ability to achieve very high extractions. For this reason the comparison with milling will be restricted to this type of cane diffuser.

Table 2.2 shows the main characteristics of the South African diffuser described previously.

Table 3.2 Comparison between different kinds of diffusers

Factory	Diffuser	Throughput tch	Effective Screen area m^2	Length m	Width m	Outside diam. m	Outside diam. m	Cane Crushed tch
Malelane	De Smet	225	160	33.2	7			225
Pongola	Van Helen 5 cell	150		-	-			-
Umfolozi	Saturne	150			4	12	9	80
Empangeni	BMA 1 F& S cell	225	170	35.4	4.8			203
Entumeni	De Smet	90	59	73.6	2.49			48
Union Co-op	BMA	108	48	28	2.2			60

Source: Allan (1973)

2.3.4 Operating factors affecting sucrose extraction in a cane diffuser

The effect of temperature, chain velocity, and cane bed height on sucrose extraction efficiency is described below:

Temperature

The higher temperatures in a diffuser cause gelatinization of starch granules, which render the starch available to natural enzymes in the cane which eliminate starch (BOYES, 1960). It also leads to higher juice colours. However, McMaster (1975) showed that losses due to thermophilic bacteria were high, therefore temperature should not drop below 80°C in the diffuser, and it helps rupture juice cells that are not opened in the cane preparation. Thus, temperature control loops are required on scalding juice heaters to obtain a temperature around 95-98°C and a certain flow rate is required to flatten the cane feed into an even bed inside the diffuser.

The scalding juice is normally split between the scalding juice tray and the back plate where the prepared cane falls into the diffuser. It is important that the scalding juice is applied as close as possible to the cane feed into the diffuser.

pH control

Generally, two pH control loops are necessary for controlling corrosion and inversion. The addition of lime in the diffuser was discontinued since the loss of sucrose due to low pH inversion on extraction is minimal (MUNSAMY; BACHAN, 2006).

Cane bed height

The height of the average bed is 1. 5 meters. This is an operating parameter and is adjusted according to the throughput and percolation characteristics of the bed. During rainy periods when percolation is poor a lower bed height/faster bed speed is required. Generally, extraction improved with a higher bed level. Bed level should be sufficiently high for the dewatering drum to give the bagasse bed a good squeeze. Likewise, the maximum diffuser bed speed will be set by the ability to the dewatering mills to handle the amount of bagasse in the diffuser. The chain drags the cane bed at a rate of about one meter per minute.

Recycle Mud

The recycle mud appears as a solution when the filter station cannot filter the mud due to its consistency and variable thickness. The advantages of mud recycle are zero filter-cake losses, decommissioning of the filter station, elimination of microbiological and spillage losses across the filter station. Added benefits are thermal efficiency due to zero filter wash water, zero bagacillo usage and fuel value of filter-cake.

The zero filter wash water allows more imbibition water for the same evaporator capacity. An added advantage of mud recycle is a clean smelling factory where it increases cell pH from an average of around 5.5 to 5.8 across the diffuser.

Diffuser chain

Munsamy and Bachan (2006) give some recommendation about diffuser chain maintenance since the Sezela and Umzimkulu experiences have shown that the chain pins and bushes need to be replaced every 6-8 years, and the chain needs to be replaced every 12-16 years.

The chain runners inside the diffuser require replacement every two seasons. This is an important maintenance function, as worn runners can cause bagasse particles to lodge themselves between the chain and runner and eventually lift the chain off the drive sprockets.

The drive sprockets need to be built up to the original profile every two to three seasons. An approved welding technique must be used and a qualified artisan under close supervision must do the work. It is also important that the earth lead of the welding machine is attached as close as possible to the sprocket to avoid electric current arcing of the drive shaft bearings. It is recommended that all future installations have the return chain on idlers to avoid dragging a hot, dry chain on a runner.

If long stops are encountered due to mechanical breakdowns, it is generally advisable to empty the diffuser if the stop is to last more than about six hours. If this is not done, significant deterioration of the sugar in the diffuser can occur.

Diffuser feeding

There are three methods to control cane feed rate control into a diffuser (REIN, 1995).

- Adjusting the speed of feed rolls beneath a choked feed chute feeding into a shredder ahead of the diffuser.
- Using a belt weigher, and adjusting the belt speed to give a constant mass flow.
- Measuring the depth of cane on the belt conveyor feeding the diffuser, and controlling the speed of the belt to keep the product of conveyor speed and height constant.

Maintenance

Annual maintenance required on diffusers is minimal, involving checking and inspecting screen condition, chain, and chain runner wear, and bed disturbance screw flight repair. Where a diffuser chain either has to be replaced or have new pins and bushes installed periodically, between 5 and 20 years, depending on the design of the chain (REIN, 1995):

2.4 A Comparative analysis between diffusers and mills tandem

Although the diffusers have proven to be more cost-effective than the mill tandem, mills are still the main extraction system in Brazil, in which statistics show that in 2011 of 455 total mills 23 are diffusers corresponding to 5.05% of the extraction systems.

On the other hand, during the technological development of mills tandem several factors such as crushing capacity, extraction and reliability have been optimized, however, maintenance is a critical issue because the sugar factories are located in isolated areas away from the supply of parts and maintenance personnel. For this reason, diffusion technology is likely to have been more widely accepted.

The main features of the two extraction technologies are described below: mill tandem and diffusers. The use of mills is more profitable than the use of diffusers in aspects such as the reliability and the pre-processing of the cane because the diffusers are more sensitive to the interruptions and require greatest cane preparation than the mills tandem. However, the cane juice requires the greatest treatment using a mill tandem for the extraction process. Table 2.3, shows the main differences between the diffuser and the mill tandem.

Table 3.3 Comparison between diffuser and mill tandem

	Capital Cost	Extraction	Energy Consume kW/tfh	Maintenance Cost	Preparation index	Bagasse humidity
Mill Tandem	100%	97%	90	100%	90	Dry
Bagasse diffuser	85%	98%	65	80%	96	-
Cane diffuser	70%	98%	45	60%	96	Wet

Source: Rein (1995)

In terms of energy consumption: mill tandem consume more mechanical energy than diffusers, however, diffuser consumes more thermal energy than the mill tandem.

Diffusers were adopted due to the ease of varying milling capacity since it depends on the width and height of the cane bed and it does not depend on the rotation, the diameter and the length of the rolls in the case of the mill tandem.

In economic context, Sorrila *et al*. (2008) shows that under specific initial conditions (% in bagasse values among others) the mill returns a Net Present Value (NPV) and a Return Rate greater than the diffuser. However, Rein (1995) shows that capital costs and maintenance costs are lower using diffusers than mills tandem.

The capital cost advantage of diffusion increases as higher extractions are sought. These ratios are reduced if pressure feeders are required on the dewatering mills in order to achieve acceptable bagasse moistures, but are increased if a pressure feeder enables only one dewatering unit to be used.

2.4.1 Juice characteristics

Rein (1995) states that, on average, diffuser juice colours are about 25% higher than those from a milling tandem and that starch content is much lower and with lower suspended solids. This depends on the cleanliness of the cane and the diffuser temperature but can be a disadvantage when attempts are made to produce a low colour raw sugar or white sugar. Juice from the diffuser has a lower purity, but this may be partly due to the higher extraction.

In addition, lactic acid, a good indicator of microbiological activity is significantly lower in diffuser juice. Low brix raw juices degrade readily as a result of microorganism activity. At room temperatures, a large range of organisms will ferment sugar juices (MCMASTER; RAVNO, 1977).

Experiments in the laboratory have established an approximate conversion equivalence between lactic acid formed and sucrose lost (MACKRORY *et al*., 1984) thus the lactic acid content in mill raw juice can easily be twice that in diffuser juice even when the temperature is controlled.

It can be concluded that the change of the traditional milling systems by diffusers should increase 3 to 6 % the sugar production at a very reasonable cost (VAN HENGEL, 1990).

2.4.2 Operating conditions

Due to the long residence time of cane in the diffuser, start-up and liquidation operations are rather more prolonged in a diffuser. It is a common practice to fill all the stages of the diffuser with water before starting up so an adequate supply of water is necessary during the maintenance shutdown. Then there is a period of about an hour before bagasse gets through to the boilers. This means that an adequate bagasse store and system of reclaiming bagasse to the boilers is necessary.

Likewise, on shutting down, liquidation of the diffuser takes a much longer time and the clarifiers generally have to handle a reducing brix juice during the liquidation. In operation, diffusers are more flexible than mills in coping with a wider range of throughput rates.

2.4.3 Supervision

Once in steady operation, a tandem of mills requires more routine supervision than a diffuser. The large pressures and forces involved in milling require that frequent attention is given to the mills, and periodic adjustments are needed such as wear of rolls, trash plate etc. A diffuser, particularly with an automatic spray position control system installed, requires virtually no supervision once running steadily.

2.4.4 Steam balance

Additional heat is required in the diffusion system, generally obtained from either of the two vapours or vapours II bled. The net effect after evaporation is to increase the total amount of steam required in a conventional sugar mill by about 3% on cane. Generally, the diffuser requires more steam than the mill tandem, except for the case of low-pressure boilers diffuser (REIN, 1995).

2.4.5 Bagasse

One disadvantage of the diffusion is the fact that more sand that arrives with the cane ends up deposited in the final bagasse and decreases the mixed juice. The effect of this is to reduce marginally the calorific value of the bagasse but a more serious disadvantage is the fact that the additional sand in the bagasse leads to considerable wear in the boilers.

The effect of this can be minimised by changes in the design of the boiler generating tube banks. On the other hand, less sand in draft juice leads to less mud and a lower loss in the filter cake.

2.4.6 Number of operators

A change from mill tandem to diffuser at Maidstone Mill resulted in a drop in the number of operators from 5 to 2 per shift. Off-crop maintenance labour requirements for a milling tandem are halved by the installation of a diffuser (REIN, 1995).

2.4.7 Expansion of mill and diffuser capacity

Small increases in capacity can be obtained from a milling tandem by fitting pressure feeders or by replacing critical milling units, as the first and the last mill with larger units, but the increase obtainable by this means is limited.

A cost-effective method of expansion involves installing a diffuser and utilising some of the existing milling units as dewatering mills for a diffuser. Rivalland (1984) has confirmed the effectiveness of this approach from a capital cost point of view.

One of the advantages of a rectangular diffuser is that it can be lengthened to increase its capacity. However, this strategy can be expensive because it requires the installation of a complete additional diffuser but, if it is envisaged that an expansion will be required at the time that a new diffuser is being installed, it is probably wise to pre-invest in incorporating head shaft and chain designs which can operate with an expanded diffuser. It is relatively cheap to increase the length of a diffuser to obtain additional capacity with this procedure.

2.4.8 Ethanol and electricity production

One of the main products of sugarcane processing is ethanol. Therefore, considering the integrated ethanol production process, when using condensing steam turbines in cogeneration systems, it is possible to produce an electricity surplus of 83.4 kWh/ton of sugarcane using mills. However, considering the same conditions, the diffusion extraction process is capable of producing an electricity surplus of 91.3 kWh/ton of cane, including also a small increase of 2 % in the ethanol production (PALACIOS-BERECHE *et al*., 2014).

Chapter 3

Monitoring juice hold - up in a cane diffuser bed using electrical conductivity - Evaluation on a plant scale

3.1 Introduction

The main systems to extract the sucrose from the sugarcane are mills tandem and diffusers: mill tandem use mechanical force to perform the juice extraction while diffusers utilise two sucrose extraction processes from prepared cane, namely (a) washing- sucrose is mechanically removed from the surface of the fibre using water and (b) diffusion - sucrose is transferred from the fibre cells (higher sucrose concentration) to the surrounding (lower sucrose concentration) extract (REIN, 2007).

The diffusers are used to reduce the velocity of the cane bed and increase the static pressure of the fluid passing through the cane bed. They are composed for a set of stages between 10 to 18 stages, the number of stages depends on the crushing capacity. Every stage has a tray where the juice is deposited and a spray to distribute the liquid in the surface of the cane bed.

To improve the extraction process in a cane diffuser the percolation rate should be optimise through the control and monitoring of the liquid holdup. Currently, operators can control the observed liquid level at the sight glass through adjust the spray position but more accurate and reliable measurements should be implemented. In this way, some researchers (ANGEL et al., 2019, LOVE, 2017, LOUBSER, 2016) confirmed that the juice content in the cane bed could be detected using a conductivity meter. However, in these papers, the experimental tests were performed in a laboratory scale or on a full-scale diffuser under restricted conditions since the conductance of the cane bed was assessed only when the recirculation pump was switched off and on, therefore, measurements of conductance under normal operating conditions were carried out in this paper. The previous assessments to monitor liquid level in a cane diffuser are not presented in the paper because their main characteristics and issues are described by Angel *et al*., (2019).

The implementation of conductance measurements is not a trivial task because the number of conductivity meters required to monitor the liquid level in the entire diffuser is unknown, therefore, the variations of the liquid level between two stages were determinate thus, if the variation of the liquid level is negligible the liquid level in the other stages can be calculate as a function of the distance between the stages and the cane bed velocity.

On the other hand, to control the liquid level there are only two options the first is to configure the spray position in recycle, which means that the liquid is increasing inside of the stage because it recirculated to the same stage from which came and the second is to configure the spray position in bypass, which means that the liquid is directed to the previous stage, so it is decreasing inside of the stage. Normally, the spray flap position is set at zero point, this means that liquid comes from the subsequent stage but percolates through the stage where it is deposited, frequently when the diffuser is fed with sugarcane the spray flap positions of all stages are in the recycle position and they are in the bypass position when the cane bed is flooded in the last stage.

As mentioned above, the conductance variations were recorded when the spray position was in bypass and recycle since it is the only parameter which can be modified to keep the percolation optimise.

The conductance measurements of the cane bed should be related to the height of the cane bed, since a value of conductance can correspond with two liquid levels. So, the variations of cane be height were recorded, these tools would provide profiles that will be used for assessing diffuser operation and performance (as per the suggestion of Matthesius (1979).

3.2 Methodology

The experimental tests were developed at the Maidstone factory in a cane diffuser design by Tongaat Hulett (the “Maidstone diffuser”). Which has 12 stages, each stage is 9 m wide, and 4.1 m length.

The Industrial conductivity meter (described in the Appendix B) was installed in the fourth stage to get measurements once the cane bed had stabilised the magnetic flow meter was installed next to the recirculation pump and its characteristics were described in the Appendix C. It was installed to compare conductivity variations with flow rate variations.

The industrial conductivity meter has three different inputs, corresponding to the first channel, second channel and the third channel, which are highlighted by the red circle in Figure 3.1.

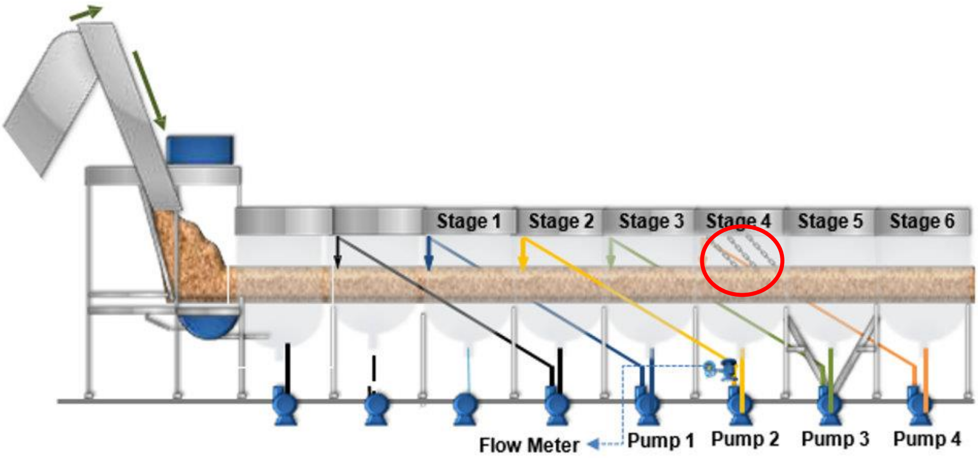


Figure 4.1 Localization of the flow meter and the three channels of the conductivity meter

Source: Oliverio *et al*. (2013)

Initially, two steel cables and one round link chain were installed to contact the surface of the cane bed. These were hung from insulated mountings on the ceiling of the diffuser to measure the conductance of the cane bed. The chain doesn't transmit current due to poor contact between the joints, but its weight is stable enough on the surface of the cane bed to provide good contact and reduce the noise in the conductance measurements. Therefore, a combination of chain and cables (i.e. a bare copper cable threaded through the links of a standard chain) was used for every channel.

The three channels are located in a line across the width of the diffuser's ceiling as shown in Figure 3.2 B and the second channel is located in the middle of the diffuser three meters away from the other channels as shown in Figure 3.2 B, a whilst the first and third channels are located 1.5 m away on either side (i.e. each 1.5 meters away from the adjacent side wall).

B

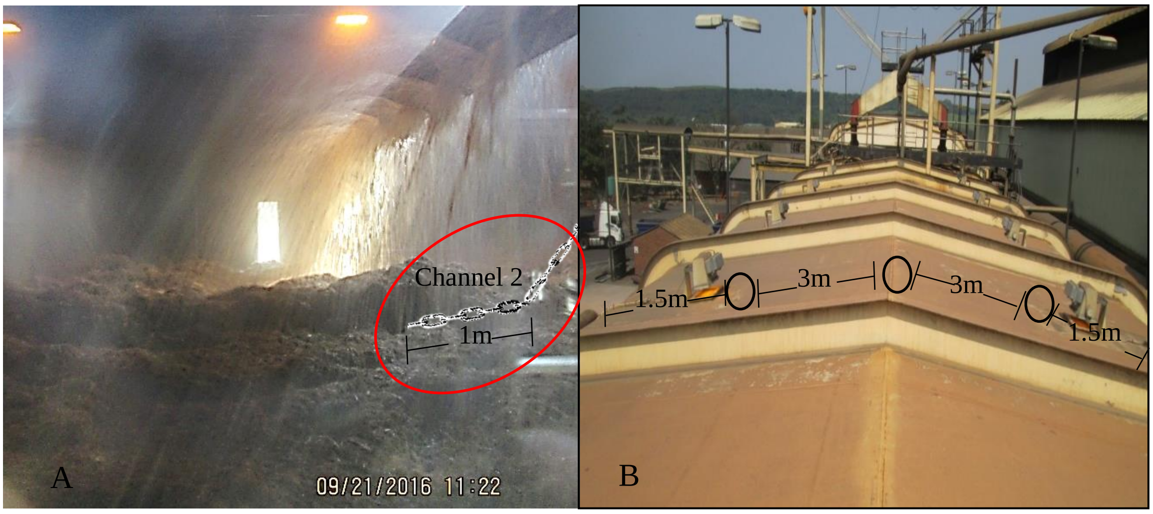


Figure 4.2 From left to right; A. Diffuser's lateral view and Diffuser's superior view

Source**:** Elaborated by the author

The chain cable devices have one-meter contact with the top of the cane bed, as shown in Figure 3.2 A, and the conductivity is measured between each chain-cable device and the body of the diffuser, the installation of the channels in the diffuser is shown in Figure 3.3. The measured conductive path is thus predominantly from the chain-cable device through the cane bed to the perforated screen below the cane bed. The industrial conductivity meter was configured in the range of 0.2 Siemens during the performance of all trials.

Figure 4.3 Installation of the chain-wire at the ceiling of the diffuser

Source**:** Elaborated by the author

The measurements of conductivity are accurate to within 1 % and to test the accuracy of the measurements of the three channels, the industrial conductivity meter measured known conductance and the variations of response of every channel was analysed. The calibration curve of the channels showed that the response of the three channels, mainly the first, slightly varied so the difference between the readings of the first channel and the second chancel is 1.95%, between the second channel and the third channel is 1.5 % and between the second channel and third channel is 2.4 %.

The flaps of stages 2, 3, 4, 5, 6 and 7 were in recycle position in all the experimental trials except in the section 3.

Characteristics of the liquid

The conductivity of the liquid in the fourth stage varies from 2200 to 2700 µS/cm at 27 °C, it depends on the characteristics of the cane and the average conductivity of the juice is 2300 µS/cm at 27 °C. The mixed juice brix varies from 9.5 % to 12 %, the pH from 5.2 - 5.3, the purity varies from 83.9 % to 86.5 % and the solids varies from 0.17 to 0.25. The density varies from 1036.8 to 1049.6 kg/m^3, it was calculate using the value of purity, and brix of the mixed juice in the web site of Jayes, 2018.

In addition, the conductivity and the temperature of the juice were measured with the conductivity meter model SC 72, its characteristics are present in Table 3.1.

Table 4.1 Conductivity meter specifications

	Description
Accuracy	± 1 of the conductivity readings and ± 0.1°C/F of the temperature readings
Range	0 to 20000µS/ cm
Resolution	0.001 µS /cm and 0.1 °C,
Temperature	0 to 80 °C
Calibration	1 point calibration/Automatic with buffer solution for min 2 calibration
Repeatability	± 2%
Resistivity	0-40.0 MΩ.cm (high purity sensor only)
Ambient Temperature	0 to 50°C

Source: Elaborated by the author

Data validation

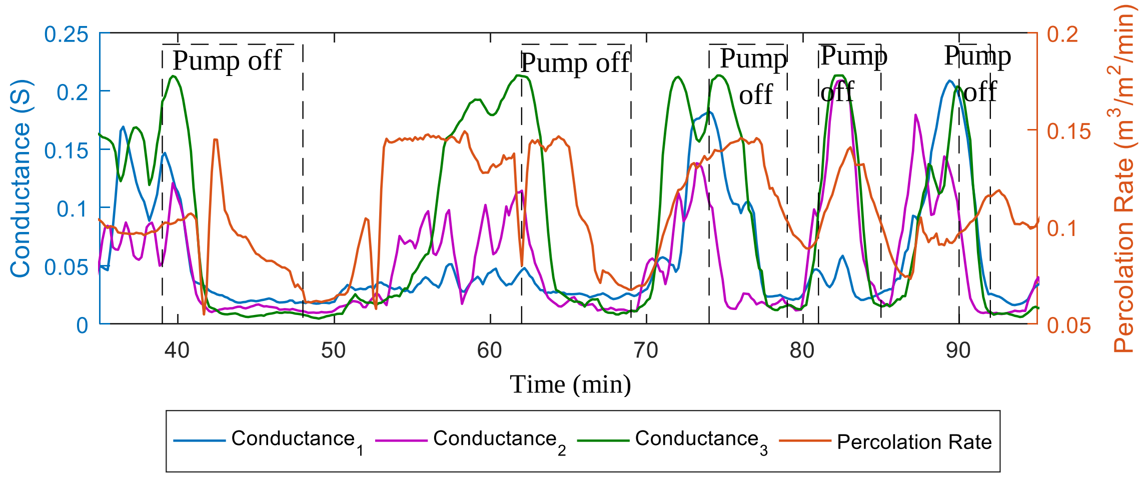
The liquid holdup is the liquid retain inside of the cane bed while the observed liquid level is the liquid observed at the sight glass. Then, the liquid level was used as indicator of the local liquid holdup since there is no other measure to evaluate this and because the liquid level is affected by the pump operation so, the liquid level decreases when the pump is turned off and it increases when the pump is turned on. However, the observed liquid level had not been used as a comparison variable for two reasons: the first is because the observed liquid level in the sight glass represent just a small area of the entire stage, but it is useful in this research because the third channels was installed was installed at 3 m from the sight glass but the conductivity meter is able to detect fluctuation at this distance so, it assessed just the local liquid level in a small region of the diffuser. The second reason is that the wall effect is unknown; however, Angel *et al*., (2017) show that this effect can be negligible.

3.3 Effect of pump operation on the conductance of the cane bed

The main objective of this experiment is to detect large fluctuations on the conductance of the cane bed during the pump operation. The number of pumps and stages are shown in Figure 3.1.

The samples of the data in Figure 3.4 and Figure 3.5 were record in different intervals of time so the average of the data in every minute was done. The pumps were deactivate

Figure 4.4. Effect of the operation of the fourth pump on the percolation rate and on the conductance of



the cane bed

Source: Elaborated by the author

The results presented in Figure 3.4 show a strong dependency between fluctuations of percolation rate and variations of conductance with the operation of the fourth pump. The conductance in Figure 3.4 varies from 0.005 to 0.21 Siemens and the percolation rate from 0.06 to 0.15 $m^3/m^2/min$. The percolation rate was compute using the area of the stage and the data recorded by the flow meter.

The black dashed line indicates when the fourth pump was turned off, which means that the liquid in the cane bed was being drained.

In Figure 3.4 and 3.5 the samples rate of the variables conductance, flow rate and percolation rate was 6 samples per minute and the sample rate of the observed liquid level was variable between 1 per minute to 1 every 9 minutes.

The data were filter with the method of moving average (MA), which as calculated by averaging a number of previous and posterior data points (coefficient filters). The coefficient filter was 6 for percolation rate and conductance.

MA= Data filter

i = Coefficient filter

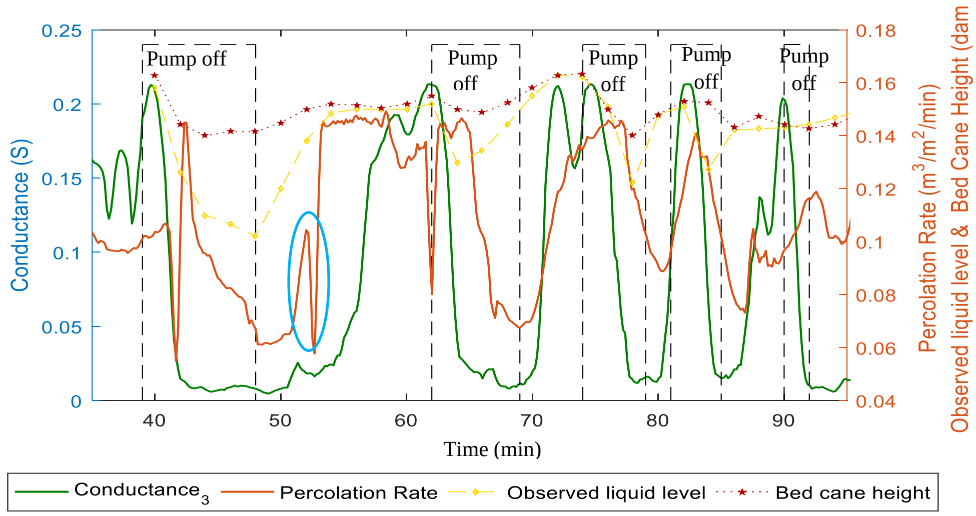
A_t =Position of the current data

$$MA = \frac{A_{t-i} \cdots A_{t-2} + A_{t-1} + A_{t+1} + A_{t+2} \cdots A_{t+i}}{2 * i}$$

The flaps of stages 2, 3, 4 and 5 were in recycle position, this means that the liquid in those stages was increased. It is important to consider that the flaps of the diffuser were not working properly because a piece of metal has blocked its free movement and as a result they were not able to clearly show the difference between the configurations of recycle and bypass positions.

The conductance of the third channel (C_3) was considered in Figure 3.5 because the measures of the observed liquid level (Z) and cane bed height (W) were recorded based on observation at the sight glass that is located next to the third channel. The data of cane bed height and the observed liquid level have an inaccuracy as data were taken manually and across long intervals; between one to nine minutes. The fourth pump was turned off for 9 minutes, 7 minutes, 5 minutes and 4 minutes the first in Figure 3.5.

Figure 4.5 Variations of percolation rate, conductance, observed liquid level and cane bed height with the operation of the fourth pump



Source: Elaborated by the author

The x-axes start in 35 minutes in Figure 3.4 and Figure 3.5 because data were recorded before of that time. The blue circle could indicate a bubble effect on measurements since it looks like this and the sample rate of the observed liquid level was variable between one samples every minute to one sample every 9 minutes, with a total of 43 samples.

The flow rate is affected for the operation of the pump but it is important to consider that the liquid takes a time to percolate the cane bed until be deposited in the trail's outlet tube where was installed the flow rate. So, considering a cane bed velocity of 0.7 m/min and an average percolation rate of 1.5 m^2/m^3/min and a cane bed height of 1.5, the liquid takes 1.1 minutes to percolate the cane bed height.

The measurements of observed liquid level were recorded based in visual inspection at the sigh glass as shown Figure 3.6.

Figure 4.6 Observed liquid level at the sigh glass.

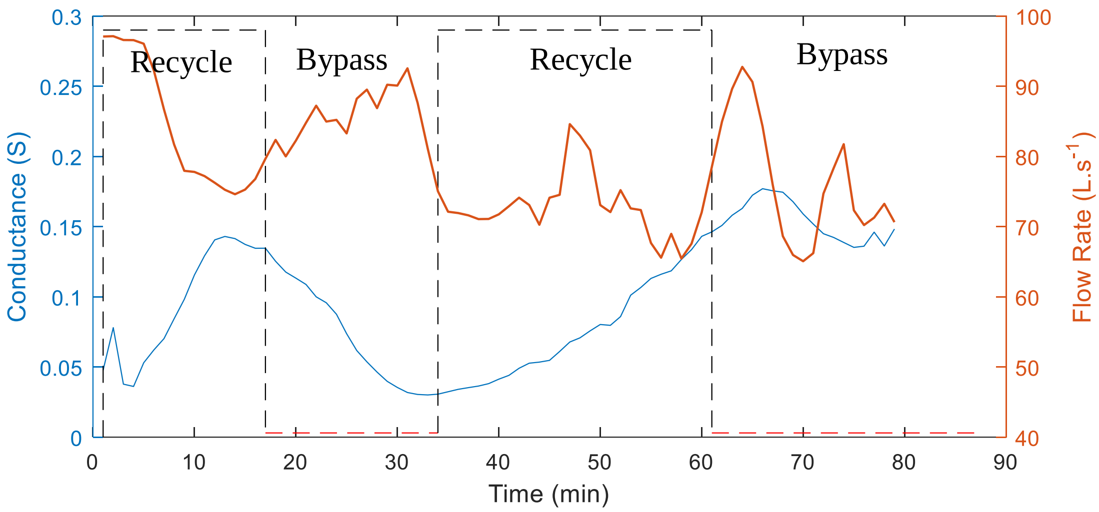
Source: Elaborated by the author

3.4 Variations of conductance and flow rate when the flap position is changed from recycle to bypass position

The conductance variations of the cane bed were when the spray's flap configuration is changed from recycle position to bypass position since these are the only configurations that can be modified to control the liquid holdup.

The conductance is the average of the conductance of the three channels (c_A) in Figure 3.7, where the conductance varies from 0.027 to 0.19 Siemens and the flow rate varies from 61 to 98 l/s. The flow rate was measured with the flow meter described in the appendix C.

Figure 4.7 Comparison between the flow rate and the average conductance of the cane bed when the flap position of the spray change from recycle position to bypass position



Source: Elaborated by the author

The dotted black lines indicate when the flap position of the fourth stage was in recycle position. These data were filtered with the method of moving average (MA), which is calculated by averaging a number of previous and posterior data points (coefficient filters). The coefficient filters were 25 and 10 for flow rate and conductance, respectively and the sample rate for both variables was 1 sample per minute.

The conductance increases when the flap position of the fourth stage is in recycle because the liquid recirculated inside of the fourth stage on the contrary, the liquid decreases when the spray is in the bypass position because the liquid is directed to the previous stage. While, the flow rate is not affected by the variation of the spray's flap position.

It is important mentioned that the results presented in Figure 3.7 were not reproducibility since sometimes the conductance did not increase when the spray was in recycle position, it could happen because the flaps of the diffuser are not working properly, they are not able to clearly show the difference between the configuration of recycle position and bypass position because a piece of metal has blocked its free movement. Further, the spray of the third stage is spraying liquid to the fourth stage when the flap of the fourth spray was in the recycle position. It was observed when the fourth pump was switched off.

3.5 Flooding detector

The aim of this experiment is to characterise and to induce flooding in the cane bed through deactivation of the recirculation pumps 2 - 4 during different time intervals between 5 to 8 minutes.

The second pump pumps liquid from the fourth stage to the second stage, the third pump pumps liquid from the fifth stage to the third stage, and the fourth pump pumps liquid from the sixth stage to the fourth stage.

The conductivity meter is able to detect flooding in the cane bed without another type of measurement since when the cane bed is flooded the conductance of the three channels remain at specific values without any fluctuations as shown in Figure 3.8, reproducibility tests were performed to confirm this result. While, other methods requires of at least two measurements to detect the flooding in the cane bed, i.e. the measurements pressure used as indicator of liquid level need the cane bed height to determinate the flooding in the cane bed.

The conductance varies from 0.0064 to 0.21 Siemens and the flow rate from 42 to 82 l/s and the sample rate was 58 samples per minute for all the variables in Figure 3.8.

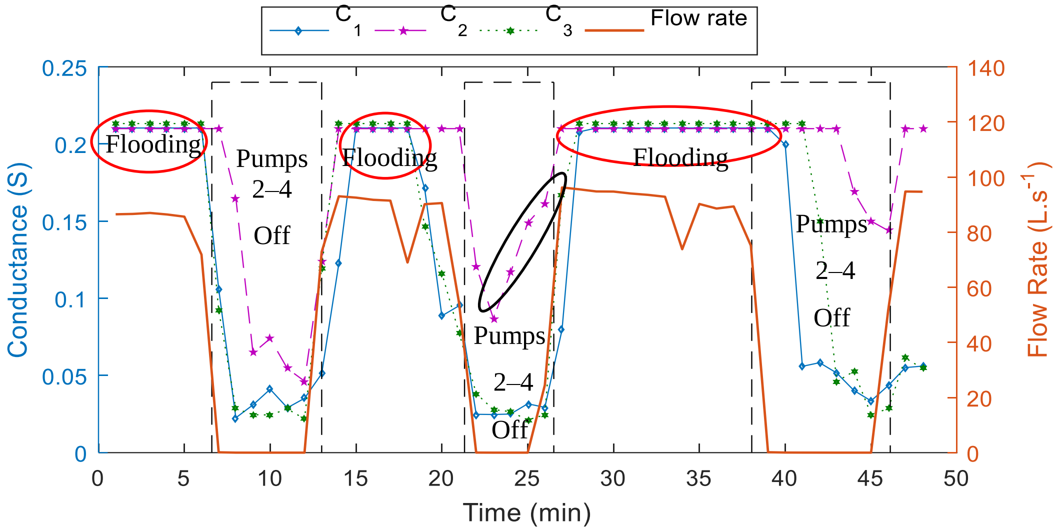


Figure 4.8 Flooding detection in the cane bed

Source: Elaborated by the author

The red circles indicate when the cane bed of the fourth stage was flooded. Figure 3.8 shows that the second channel remains longer flooded and its conductance is higher than other channels when the pump is turned off, in addition, the conductance of the second channel decrease less and less as the pump shuts off, while the other channels decrease to approximately the same value. It could happen because the third channel and the first channel are drained easier than the second channel since they are close to the diffuser's wall, besides, the current has a preferential path and it could not be of the second channel due to the location of it and the accumulated of the sugarcane at the centre of the diffuser, since it is the profile which increases the extraction in the diffuser.

When the fourth pump was deactivated the third time, the three channels take a longer time interval for the conductance to decrease because the cane bed was in flooded (12 minutes) longer than the second (8 minutes) and first time (6 minutes) that the pump was switched on.

The pumps were deactivated at different time intervals to test its effect on the conductance and on the flow rate, however, it was discovered that the minimum time interval should be three minutes otherwise the flow meter would not have time to detect the variations of the flow rate. The fourth pump was deactivated 6.4 minutes, 5.2 minutes and 8.06 minutes the first, the second and the third time respectively.

Figure 3.9 shows how a cane bed flooded looks inside the diffuser, which correspond to the straight lines shown in Figure 3.8.

Figure 4.9 A cane bed flooded

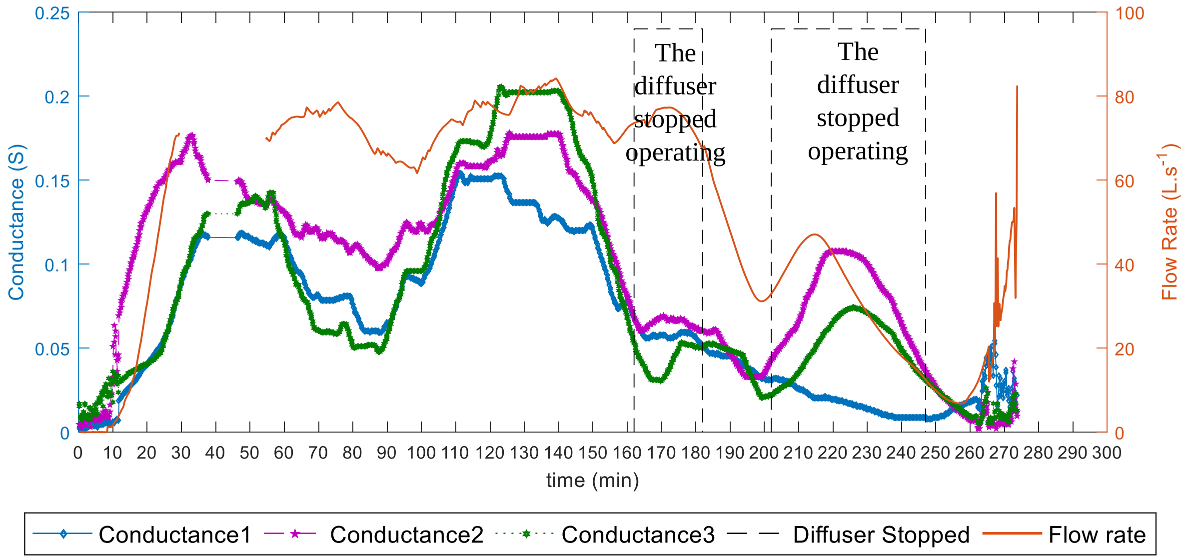
Source: Elaborated by the author

3.6 Variation of the conductance and flow rate when the diffuser was being fed with sugarcane

The measurements of flow rate and conductance began to be recorded when the diffuser was empty, subsequently, it was fed with sugarcane but the flow rate data could not be recorded during the time interval from minute 37 to minute 56 in Figure 3.10.

The diffuser stopped operating two times on this day, from minute 162 to minute 182 and from minute 202 to minute 247, as indicated by the dotted black lines in Figure 3.10, whilst recirculation pumps continued working.

Figure 4.10 Comparison between the flow rate and the mean conductance of the cane bed, when the



diffuser was being fed with sugarcane

Source: Elaborated by the author

The coefficient filters were 50 and 70 for flow rate and conductance, respectively.

The conductance varies from 0.005 to 0.21Siemens, the flow rate varies from 0 to 95.5 l/s and the sample rate was 6 samples per minute for all the variables in Figure 3.10.

The conductance of the three channels have the same fluctuations but with different values of conductance. It is important considering that the electronic board of the first channel had some electronic problems and, therefore, this channel registered the lowest conductance compared with the conductance values registered by the other channels in some experimental trials, even when the conductivity meter was calibrated so it is shown by the repeatability percentage in the methodology.

The second channel has the highest conductance perhaps by the reason mentioned in the section 3.6. As additional information, the diffuser takes approximately two hours to establish the cane bed and the average conductance of the cane bed can be altered by the formation of liquid deposits in one of the channels.

3.7 Variation of cane bed height and observed liquid level throughout the diffuser’s stage

The conductivity meters can be installed at various points across the diffuser. However, it is unknown the number of conductivity meter needed to measure the liquid level in the entire diffuser. Therefore, to determine the variation of the liquid level in the diffuser, it was monitored the liquid level in the fourth stage and the sixth stage, as shown in Figure 3.13 and Figure 3.14. If the variations are insignificant, the liquid level can be calculated using the distance between the stages and the cane bed velocity.

For the same reason mentioned above, the variation of the cane bed height through the fourth stage and the sixth stage is also presented in Figure 3.11, these measurements were not recorded in the fifth stage because the sight glass was not installed there. The sample rate was 1 sample per minute for cane bed height and observed liquid level in Figure 3.11 – 3.14.

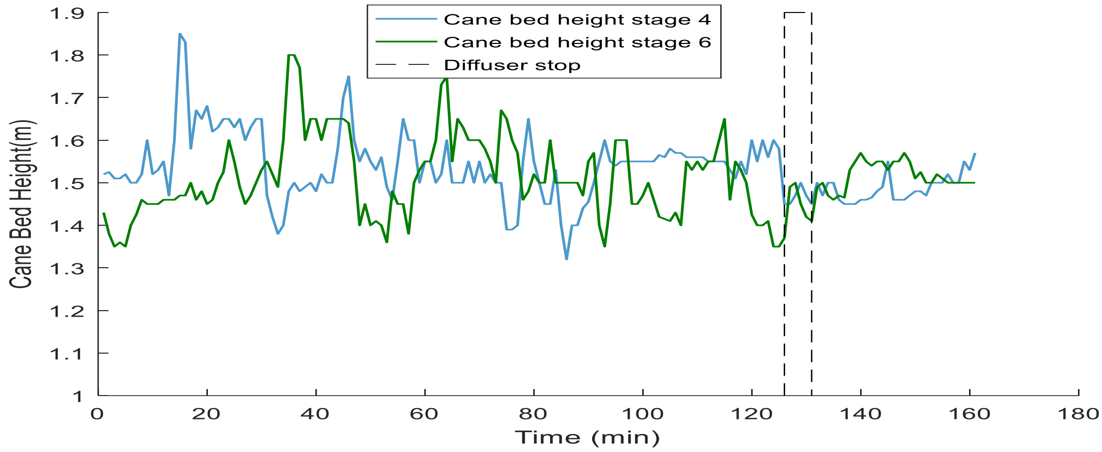


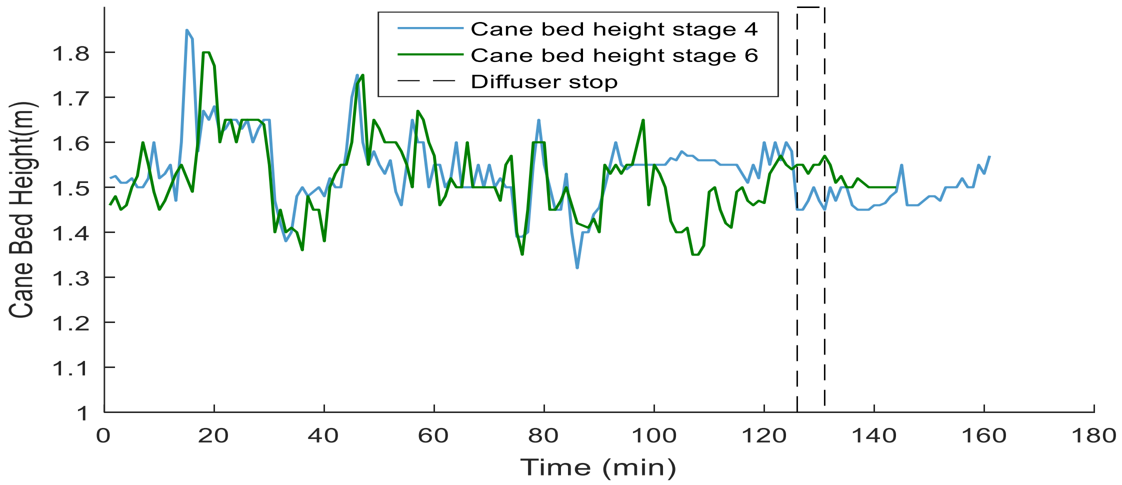
Figure 4.11 The cane bed height in the fourth and sixth stage

Source: Elaborated by the author

The conductivity meter was installed at the fourth stage because the cane is sufficiently wet and compacted in this stage. The cane height varies from 1.32 to 1.87 cm being 1.5 cm the average height.

The distance between the sight glass of the fourth stage and the sight glass of the sixth stage and the velocity of the cane bed were considered to calculate the offset time in Figure 3.12.

Figure 4.12. Variation of the cane bed height from the fourth stage to the sixth stage, considering an



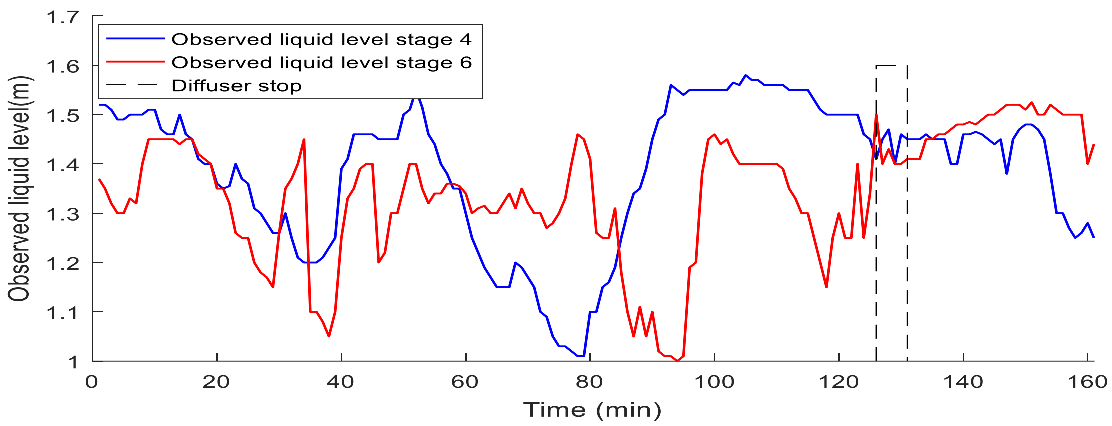
offset of time of 18 minutes in the data of the cane bed height of the sixth stage

Source: Elaborated by the author

The cane height did not vary significantly between the stages. So, the cane bed height of the other stages can be calculate using the cane bed velocity and the distance between the stages.

The variation of the observed liquid level through two stages is shown in Figure 3.13 and it uses to vary from 1 m to 1.6 m.

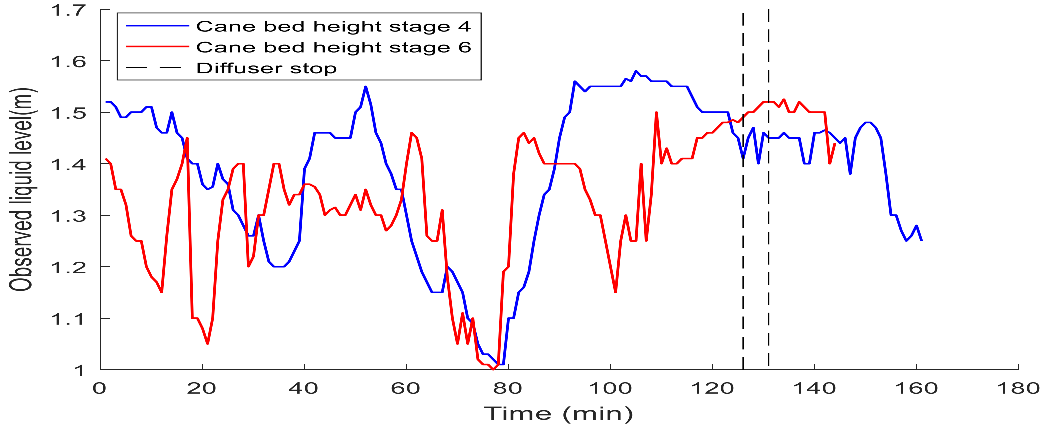
Figure 4.13 Variation of the observed liquid level from the fourth stage to the sixth stag



Source: Elaborated by the author

The time offset of 18 minutes was considered in Figure 3.14 to compare the observed liquid level in the fourth stage with the observed liquid level in the sixth stage.

Figure 4.14. Variation of the observed liquid level through the fourth stage to the sixth stage, considering



an offset time of 18 minutes in the data of the observed liquid level of the sixth stage

Source: Elaborated by the author

The observed liquid levels of stage 4 and stage 6 are completely different between each other except during the minute 65 to 83 minutes. Therefore, the conductivity meters should be installed in the mostly of the diffuser's stages.

The data presented in this document were recorded at least three times under different conditions to assure the repeatability of the results. The liquid varies a lot between two consecutives stages compared with the cane bed height maybe due to the variation in permeability, flow rate and compaction of the cane since, the cane compaction increases with washings of the cane bed.

The analysis of the results show considerable variation in the liquid level and slight variations of the height of the cane, therefore, it is necessary install several conductivity meters and a few cane height meters along of the diffuser. Although, Rein and Ingland (1979) installed equipment in six of the 16 stage of the diffuser to measure indirectly the liquid level and the extraction was improved in the last season due to high index of the sugarcane since the increase of open cells permit more mass transfer but if the liquid had not been controlled the normal consequence of the increase of cane preparations would be the flooding in the cane bed.

3.8 Variations of conductance, flow rate, observed liquid level and cane bed height under normal operating conditions

As mentioned above, it was necessary recorded data of the main variables under normal operating conditions, as shown in Figure 3.15, since previous assessments did not analysed the variation of these variables.

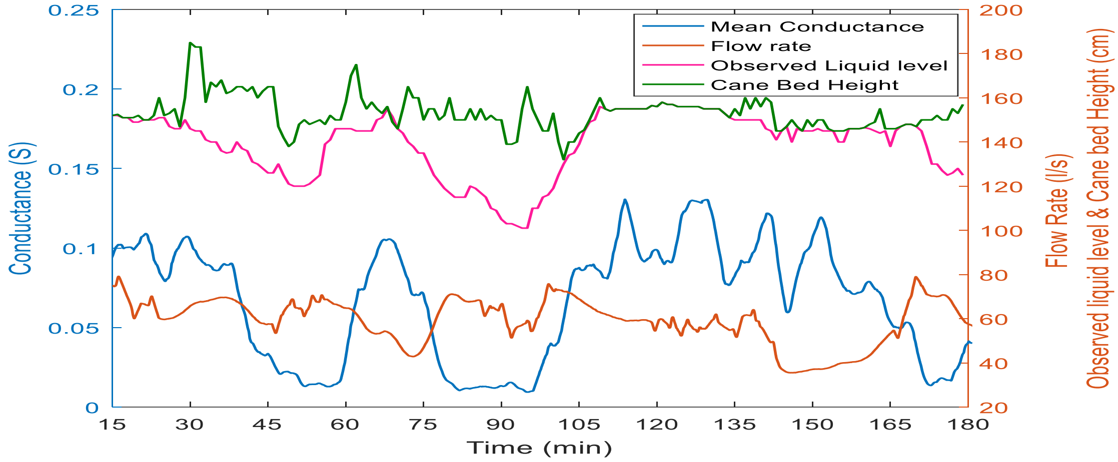


Figure 4.15. Variation of the main variables during 180 minutes

Source: Elaborated by the author

The coefficient filters were 100 and 10 for flow rate and conductance, respectively and the sample rate for both variables was 55 sample per minute. Where, the conductance varies from 0.015 to 0.135 Siemens and the flow rate from 38 to 83 l/s in Figure 3.15. The observed liquid sample rate was variable between one sample every minute and one sample every two minutes, with a total of 165 samples.

In Figure 3.16, the coefficient filters were 120 and 60 for flow rate and conductance, respectively and the sample rate for both variables was 55 sample per minute. Where, the conductance varies from 0.01 to 0.215 Siemens and the flow rate from 43 to 93 l/s.

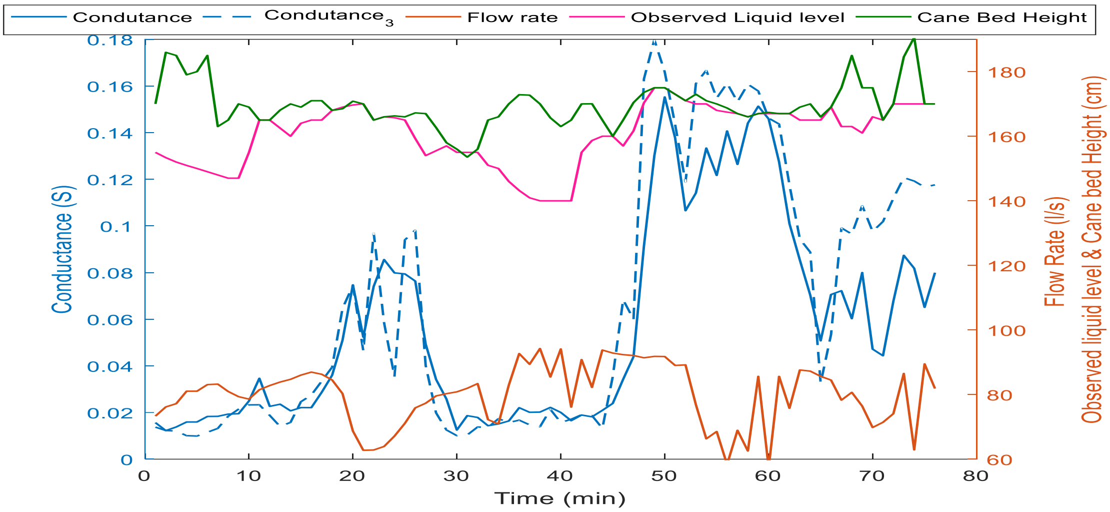


Figure 4.16 Variation of the main variables during 80 minutes

Source: Elaborated by the author

The observed liquid sample rate was variable between one sample every minute and one sample every three minutes, with a total of 75 samples.

3.9. Variation of conductance and flow rate when the diffuser stop operating

The diffuser stop to operating during 220 minutes in Figure 3.17, where the coefficient filters were 65 and 25 for flow rate and conductance, respectively and the sample rate for both variables was 6 sample per minute. The conductance varies from 0 to 0.21 Siemens and the flow rate from 0 to 89.9 l/s.

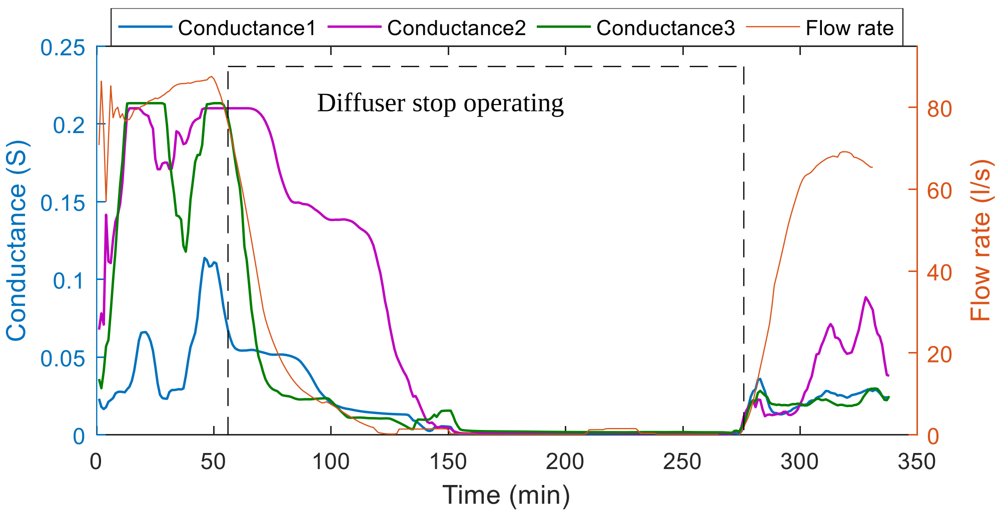


Figure 4.17 Variation of the main variables during 80 minutes

Source: Elaborated by the author

The diffuser started to be emptied (the exact minute is unknown) after it has stopped operating, so the conductance and flow tend to zero in the time interval of 150 to 275 minutes.

The conductance of the second channel is higher in Figure 3.17, due to reasons mentioned in section 3.5, since it is the same case a cane bed being drained in all the stages.

3.10. Correlation coefficients between the main variables

The correlation coefficient of the two variables is a measure of their linear dependence (Appendix D). The values of the coefficients can range from -1 to 1, with -1 representing a direct, negative correlation, 1 representing a direct, positive correlation and 0 representing no linear correlation.

The conductance of the third channel (C_3) was considered in Table 3.2 because the measurements of the observed liquid level (Z) and cane bed height (W) were recorded based on observation at the sight glass that is located next to the third channel.

Table 4.2 The correlation coefficients between the main variables

Figure	Variable	Correlation coefficients					
		W	α (%)	Z	α (%)	F_r	α (%)
Fig. 3.4	C_3	0.59	99.9	0.63	99.9	0.316	96.1
	C_A	0.41	99.4	0.54	99.9	0.31	95.1
	F_r	-0.12	55.7	0.17	73	Na	Na
Fig. 3.7	C_A	-	-	-	-	-0.29	100
Fig. 3.8	C_A	-	-	-	-	0.72	100
Fig. 3.10	C_A	-	-	-	-	0.58	100
Fig. 3.15	C_3	0.30	99.9	0.71	100	Na	Na
	C_A	0.21	99.5	0.81	100	Na	Na
	F_r	0.12	86.7	0.25	99.8	-	-
Fig. 3.16	C_3	0.21	92.8	0.74	99.9	-0.23	100
	C_A	0.12	69.5	0.72	99.9	-0.29	100

	F_r	0.04	30.8	-0.22	94.2	-	-

Source: Elaborated by the author

Where C_3 is the conductance of the third channel (S); C_A is the conductance average of the three channels (S); W the cane bed height (m); Z the observed liquid level (m); F_r is the flow rate (l/s), α represents the confidentiality interval (%) and Na represents no relationship between the variables.

The correlation coefficient between the flow rate and the mean conductance in Figure 3.8 was the highest value in Table 3.2 because pumps 2 – 4 were deactivated and the flow rate was measured in the second pump so when pumps were turned off the conductance decrease and the flow rate was zero. In addition, the deactivation of pumps 2 to 4 ensures that the adjacent stages did not alter the normal operation of the fourth stage, on the contrary what happened when only the fourth pump was turned off (Figure 3.4) since the flow rate and the conductance doesn't have any relationship because the adjacent stages may not allow the drainage of the cane bed.

The flow rate and conductance are affected by the operation of the fourth pump since when it is deactivated both decreases but not at the same time neither in the same way because the liquid takes time to percolate the cane bed, and sometimes the flow meter cannot register the variation of the liquid level because the pump was switched off for a short time interval besides the bubble effect also influence these results.

Therefore, it can be concluded that, under extreme conditions, such as when the recirculation pumps (2 - 4) are deactivated, when the diffuser stops operating, when the diffuser is being fed with sugar cane, (in this experimental trial the diffuser stopped operating two times for 20 min and 45 min and the data were recorded for 279 minutes) conductance and flow rate have similar fluctuation and a high correlation coefficient (see correlation coefficient in Figure 3.8 and 8). While the correlation coefficients in Figure 3.7, 13, 14 show that there is no relationship between these variables under normal operating conditions and even when only the fourth pump is deactivated these variables don't have any correlation (see the correlation coefficients in Figure 3.4).

The conductance of the three channels and the flow rate have the same fluctuations under special conditions because these conditions isolate the effect of adjacent stages on the fourth stage (the stage where conductance and flow rate measurements were carried out), i.e. when the diffuser is fed the cane bed, it takes almost two hours to operate normally, therefore, the effects of the subsequent stages are negligible in the first minute when the diffuser is fed.

When the diffuser stops operating, it became in a stationary system, where the same variety of cane is washing several times, so the possibilities of changes due to the characteristics of the cane are reduced, in addition, the results performed at laboratory scale showed that conductance and flow rate have the same fluctuation in steady state.

The correlation coefficients also show that the cane bed height has no relationship with any variable (conductance, flow rate, and observed liquid level) as well as the flow rate does not have a strong relationship with the observed liquid level.

On the other hand, a statistical analysis depends on the number of samples and the sampling time, these factors were the main issue for the manual collection of the observed liquid level data while the conductance and flow rate do not present this problem since the sample rate was between 6 to 55 samples per minute.

As mentioned before the correlation coefficient between the observed liquid levels (samples total 165) and the conductance in Figure 3.15 is higher than the correlation coefficient between the observed liquid levels (samples total 75) and the conductance in Figure 3.16.

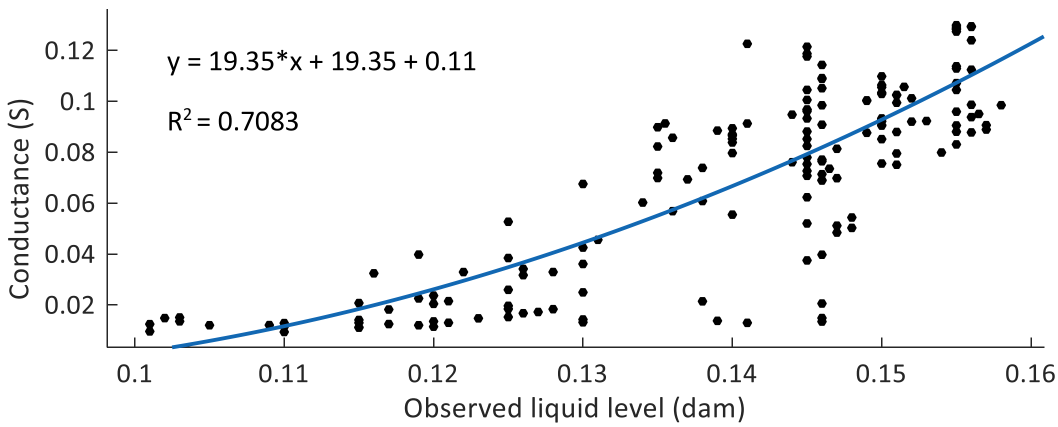
3.11 Relationship between the variables

The aim of this section is determinate the relationship between the conductance and the observed liquid level and between the flow rate and the observed liquid level to achieve it these variables were plotted and it was found the trend line which fit better with the experimental data.

The collected data of observed liquid level were recorded every two minutes (short time interval), therefore, the samples of observed liquid level were few to make a statistical analysis and determine the relationship between the variables. Thus, data from other days were taken to make the statistical analysis and get the correlations between the variables.

The samples of the data in Figures 3.18 - 3.20 were record in different time intervals so the average of the data every minute was calculated. The conductance was plotted as a function of observed liquid level, as shown in Figure 3.18. These data were recorded during 164 minutes.

Figure 4.18 Relationship between the conductance and the observed liquid level



Source: Elaborated by the author

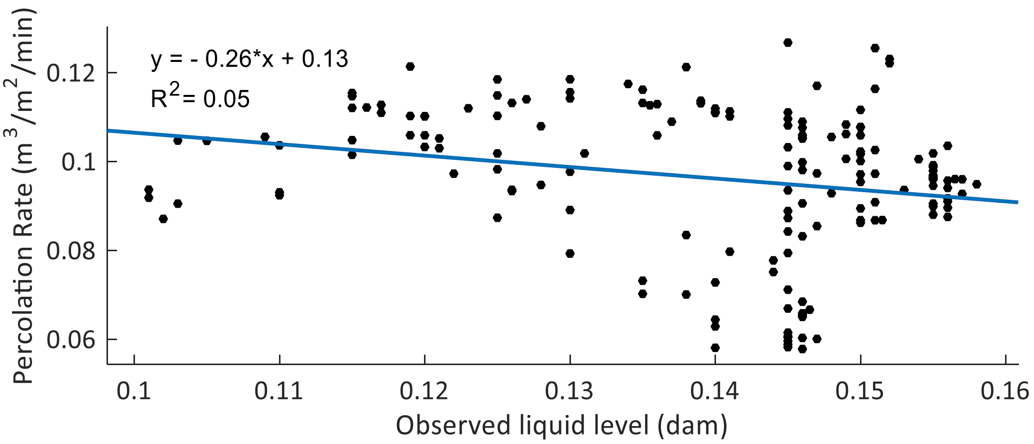
The data from Figure 3.18 and Figure 3.19 were filtered with the method of moving average (MA), which is calculated by averaging a number of previous and posterior data points (coefficient filters). The coefficient filters were 100 and 80 for percolation rate and conductance, respectively.

The response time of the variables should be considered since the conductance response time is instantaneous while the percolation rate response time is not. The response time is defined as the time needed by the flow meter or the conductivity meter for detecting the fluctuations of percolation rate or the conductance in the cane bed.

Loubser (2016) and Love (2017) studied the conductance through the cane bed as a measurement of liquid holdup, and similar results were found. These results are presented in Figure 3.7 and Table 3.2, for the conductance and flow rate for trials done in the laboratory on a glass tank diffuser using a conductivity meter, a data logger.

Figure 3.19 shows a linear relationship between the observed liquid level and the percolation rate with a root mean square of 0.05.

Figure 4.19 Relationship between the percolation rate and the observed liquid level

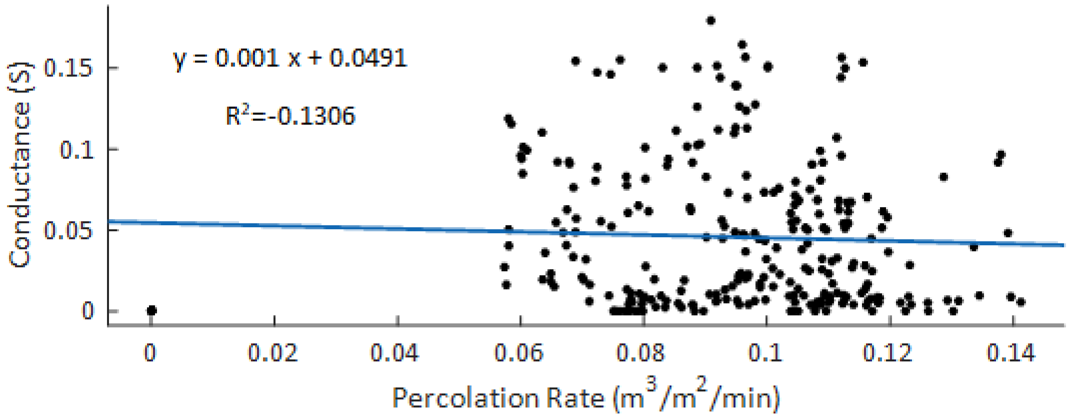


Source: Elaborated by the author

It is also important to consider that the amount of liquid in the bed of cane in every stage depends on many factors such as the spray flap position, the percolation rate of the liquid through the cane bed, and the horizontal velocity of the cane bed. If the cane bed velocity was too low the liquid could be deposited in the previous stage or if it was too high the liquid could be deposited in the subsequent stage. Other factors such as characteristics of the cane and the preparation index of the cane modified the permeability of the bed therefore the percolation rate through the cane bed was modified.

The data in Figure 3.20 was not filtered to evidence the direct relation between the conductance and the percolation rate.

Figure 4.20 Relationship between the percolation rate and the conductance



Source: Elaborated by the author

The data were plotted using the program Matlab in Figure 3.18 - 3.20, where the blue line is the tendency curve corresponding to a first order polynomial equation. The robust method used to find this polynomial was the Bisquare weights in Figure 3.20 and Figure 3.7. This method minimises a weighted sum of squares, where the weight given to each data point depends on how far the point is from the fitted line. Points near the line get full weight. Points farther from the line get reduced weight. Points that are farther from the line than would be expected by random chance get zero weight. This method seeks to find a curve that fits the bulk of the data using the usual least-squares approach, and it simultaneously minimises the effect of outliers. Therefore, the RMS is high because the outliers have a low weight in the linear regression curve.

On other hand, conductance, percolation rate and observed liquid level have a direct relationship and these variables are interrelated. However, in some cases, the percolation rate could not have a direct relationship with the conductance in the experiments performed on the diffuser because the flow meter measures the flow of the amount of liquid deposited in the tray of the fourth stage. Sometimes the liquid in the cane bed could go back and forth from preceding or subsequent stages without being deposited in the tray of the fourth stage, where the flow rate is measured, i.e. considering that the flow rate is measured in the fourth stage, if the fourth stage is in flooding, but the fifth stage or the third stage are in normal conditions, the liquid of the fourth stage could be deposited in the tray of the third stage or in the tray of the fifth stage. Therefore, the conductivity meter recorded data of high conductance and then a decrease of conductance while the flow meter could not measure the high flow rate because the liquid flowed to the tray in another stage.

Chapter 4

Pressure distribution in a porous medium as an indicator of the observed liquid level

4.1 Introduction

The objective of the extraction process is to separate the sucrose-containing juice from the remainder of the cane, mainly fibre. Extraction systems usually adopted are mills tandem and/or diffusers (PALACIOS-BERECHE *et al.*, 2014), however, the diffuser presents higher efficiency, lower energy costs, lower maintenance and lower capital costs than mills tandem (FABER, 2013). For example, Van Hengel (1990) observed that the change of the traditional milling systems by diffusers increased the sugar production from 3 to 6 %, at a very reasonable cost.

Diffusers utilise two sucrose extraction processes from prepared cane, namely (a) washing- sucrose is mechanically removed from the surface of the fibre using water and (b) diffusion- sucrose is transferred from the fibre cells (higher sucrose concentration) to the surrounding (lower sucrose concentration) extract (REIN, 2007). Where, the extraction is carried out in counter current, so, the imbibition water is added in the last stage, and this is mixed with juice extracted from that stage, subsequently, the liquid is pumped through to all stages until the second stage.

The diffuser is composed of stages and the number of stages depends on the crushing capacity of each diffuser. The diffuser were carried out the test, the ‘Maidstone diffuser’, has a capacity of 300 Tons of cane per hour (THC) and it has 12 stages; each stage is 9 m wide and 4.1 m in length.

Stages are characterized by having a tray to collect the liquid at the screen of the diffuser, the screen is a perforated plate to filter the juice from the cane bagasse and it is located at the bottom of the diffuser. The stage also have a spray to distribute the juice at the top of the sugarcane bed, the spray deflector device adjust the flap to bypass position or recycle position; the latter means the liquid flows through the same stage and the first means that the liquid goes to the previous stage. The operator can control and adjust the spray deflector position based on visual inspection of the observed liquid level at the sight glass. However, this adjustment should be automated because the manual adjustment requires 12 operators working as long as the diffuser is under operation.

The visualization of the observed liquid level at the sight glass is not an accurately measure because the viewable area of the sight glass only allows the observation of the liquid level near the side walls of the diffuser. Moreover, the measurement cannot be done in all the stages because the sight glasses are not installed in all of them or because sometimes the sight glass is damaged, compromising the visibility. The liquid holdup does not have a stable level as it changes throughout the cane bed and along the diffuser. Fast fluctuations of the observed liquid level are a critical problem because the operators record the data manually. Therefore, the observed liquid level should be assessed online in order to estimate the optimal percolation rate enabling sucrose extraction and avoid flooding in the cane bed. In this way, some experiments have been carried out to measure the observed liquid level in the cane bed through manometers, conductivity meters, and floating devices. The floating devices are not suitable for this application because the diffuser must be flooded so the floating device can lay on the cane and the use of conductivity meter and manometers are still under research phase.

The pressure was measured for the first time on a plant scale in South Africa at Amatikulu mill using a pressure transductor installed on the wall of the diffuser. Afterward, pressure transmitters with a flush mounting diaphragm were installed at the wall of the diffuser at Felixton mill. The electronic pressure transmitters were installed vertically, at distances of 0.45, 0.85, 1.050 and 1.45 m above the screen, and the pressure profile down the bed was calculated by the Carman-Kozeny Equation (Rein and Ingham, 1992).

The use of the pressure transductors as indicator of the observed liquid level was assessed for two seasons in six of the 16 stages at Amatikulu mill, in order to adjust and control the spray deflector position. The extraction was improved in the last season due to high index of the sugarcane since the increase of open cells permit more mass transfer but if the liquid had not been controlled the normal consequence of the increase of cane preparations would be the flooding in the cane bed.

According to Rein and Ingham (1992), the cost of automation of the diffuser's sprays is justified by the reduction of the imbibition liquid and the coal used to heat it, so the installation of the pressure transductors would be paid within a quarter of the season. Although the results were used to create a patent, these were particularly noisy and questionable, therefore this method was not widely accepted.

Loubser and Jensen (2015) used a rectangular model of the diffuser (The tank had a glass front which was 1.5 m long and 1 m high) to map the pressure distribution and flow through a bed, these experiments were conducted at laboratory scale. They found that the friction pressure loss exactly matches the gravitational pressure at steady state. So, it can be concluded that the static pressure has a slight variation associated with the distribution of permeability, so, the pressure cannot be used as an indicator of liquid holdup.

The results from these two investigations differ among themselves because one was performed in a plant scale while the other was performed in a laboratory scale in steady state, considering the same quality, variety of the cane and without consider the effect of the adjacent stages, therefore, permeability effects were not perceptible because probably the compaction of the cane could not be the same as in the diffuser.

On the other hand, the pressure profiles were created based on different functions of permeability (BREWARD *et al*., 2011) and using Darcy's law. So, to determinate the behaviour of the permeability, several mathematical functions were tested in this paper, considering that the permeability and the compaction of the cane vary over the cane bed and create different pressure profiles. Where a linear function of permeability was used to validate this theoretical model through the experimental data, and, in this way, determinate if the observed liquid level can be assessed through to pressure variations, simultaneously assessing the permeability effects on the variation of the pressure.

4.2. Experimental procedure to measure the liquid levels on the manometers

The experimental trials were performed at the Maidstone diffuser using four manometric tubes manometric tubes installed on a diffuser wall at four different heights. These four pressure tapings points were installed on the wall of the diffuser, where four sockets (127 mm), nipples and isolation valves were installed adjacent to one of the sight glasses.

The sockets were fitted with transparent plastic tubing and were located in the cane bed, oriented perpendicularly to the flow direction and providing measurements relative to a reference atmospheric pressure, as shown in Figure 4.1, these sockets could be removed to be cleaned, thus preventing the bagasse blocking the flow of liquid in the tube.

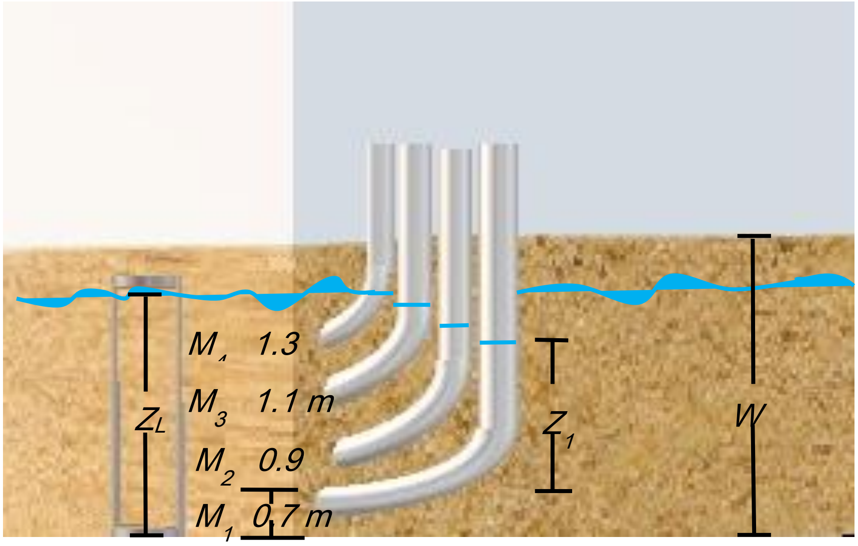
Figure 5.1. From left to right; Installation of the manometric tubes in the wall of the diffuser, they were located near to the sight glass to make a visual inspection of the observed liquid level

Source: Elaborated by the author

The plastic tubes were fixed on a wooden panel to visualise the liquid level measured by manometers installed at different heights in the diffuser's wall. Therefore, depending on the liquid level some manometers were not able to record data. There are two liquid levels; the observed liquid level were recorded based on observation at the sight glass in the fourth stage and the liquid level recorded based on observation at the four manometric tubes installed at the diffuser`s wall.

The manometric tubes and their localization in the wall of the diffuser are shown in Figure 4.2. Where the grey rectangle represent the sigh glass were the liquid level was observed (Z_L), W is the cane bed height and Z_1 is the liquid level observed in the first manometric tube considering its localization.

Figure 5.2 Manometric tubes installed in the wall of the diffuser at the fourth stage



Source: Elaborated by the author

The resolution of the manometric tubes is unknown since the liquid level never decrease to level less than 0.9 m, however, the maximum liquid level measured on the manometers corresponds to the height at which they were installed.

The manometric tube (P_1) was not working, so these data were not considered in the analysis of the results. It is essential to consider that maintenance of the system must be done frequently in order to avoid bagasse blockages of the plastic tube. Figure 4.3 shows the manometric tubes after of one year without maintenance.

Figure 5.3 Manometric tubes installed in the wall of the diffuser after one year without maintenance

Source: Elaborated by the author

Although the pressure as indicator of liquid level in a cane diffuser was assessed in the paper of Rein and Ingham (1992), some experiments were carry on to determinate the relationship between these variables under normal operating conditions and under special conditions, such as, when the recirculation pump is turning off. This pump is responsible for pumping the liquid to the stage in which the liquid level on the manometer was measured.

The liquid holdup is the liquid retain inside of the cane bed while the observed liquid level is the liquid observed at the sight glass. Then, the liquid level was used as indicator of the local liquid holdup since there is no other measure to evaluate this and because the liquid level is affected by the pump operation so, the liquid level decreases when the pump is turned off and it increases when the pump is turned on. However, the observed liquid level had not been used as a comparison variable for two reasons: the first is because the observed liquid level in the sight glass represent just a small area of the entire stage, but it is useful in this research because the manometric tubes were installed at 50 cm from the sight glass and it assessed just the local liquid level in a small region of the diffuser. The second reason is that the wall effect is unknown; however, Angel *et al*., (2017) show that this effect can be negligible and the conductance can be used as a measure of the liquid level.

Cases 1 - 4

Case 1 and case 2 correspond to the variation of pressure when the liquid inside of the cane bed is being drained by deactivation of the pump fourth, this is responsible for spraying liquid on the surface of the cane bed. Case 3 and case 4 correspond to the variation of pressure under normal operating conditions.

In addition, the MSE is the mean square error between the observed liquid level (Z) and the pressure, The calculations of the error MSE were calculated as:

$$\text{sse} = \text{Theoretical data - mean(experimental data)}^2$$

$$\text{ssr} = \text{Theoretical data - (experimental data)}^2$$

$$\text{MSE} = 1\text{-ssr/sse}$$

Permeability profiles

To determinate the distribution of pressure along to the cane bed in the fourth stage, different permeability function were tested and the experimental data were compared with the theoretical data to determinate the error of the mathematical model.

Characteristics of the liquid

The conductivity of the liquid in the fourth stage varies from 2200 to 2700 µS/cm at 27 °C, it depends on the characteristics of the cane and the average conductivity of the juice is 2300 µS/cm at 27 °C. The mixed juice brix varies from 9.5 % to 12 %, the pH from 5.2 - 5.3, the purity varies from 83.9 % to 86.5 % and the solids varies from 0.17 to 0.25. The density varies from 1036.8 kg/m^3 to 1049.6 kg/m^3, it was calculate using the value of purity, and brix of the mixed juice in the web site of Jayes, 2018. An average density of 1049.6 kg/m^3 was used in the computational simulations.

The density of the system cane-liquid was not considered because the variation of the compaction of the cane bed is unknown due to multiple and successive washes and the effect of the lifting screw.

4.3 A mathematical model to calculate the pressure

To describe the flow of the liquid through to the cane bed, Darcy's equation (BEAR, 1972; HARR (1990) were used because describes the flow of a fluid through a porous medium as the cane bed. It is assumed that the juice is sprayed at rate high enough to ensure that the cane bed is saturated, that means that the observed liquid level should the same as the bed level, and there is sufficient flooding of the top surface resulting in a unidirectional vertical flow. Equation 4.1 gives the fluid velocity (m/s) in terms of the negative gradient of the pressure (Pa) as a function of the observed liquid level (z).

$$u = -k(z)\nabla\emptyset \qquad (4.1)$$

The negative signal in Darcy’s equation means that the hydraulic level always decreases in the direction of the flow. Where μ is dynamic viscosity (Pa.s), k is permeability of the material (m/s) and $\nabla\emptyset$ is a measure of the variation of potential of the fluid. It is defined as the height to which water can rise in a manometric tube.

Potential theory is used to predict the flow in a porous medium such as prepared sugarcane. The equation of the potential is given by Equation 4.2 (KAY; NEDDERMAN, 1985).

$$\emptyset = p - pgz + \not{\rho}\frac{\not{v}^2}{2} \qquad (4.2)$$

p is pressure (Pa), which is given by the fluid height above a point, the second term represent the potential gravitational, the third term represent the kinetic energy and z is the height at some reference level, ρ is the density of the liquid (kg/m^3), and g is gravitational acceleration (m/s^2) with a negative direction according with the coordinate system presented in Figure 4.4.

Considering that the flow velocities are small, since the average percolation rate is 1.5 m^3/m^2/min, the viscous effects are predominant over turbulent effects; therefore, the velocity term was neglected in Equation 4.2.

Substituting Equation 4.2 (the potential) in Equation 4.3, then, separation and discretization the variables it is obtained Equation 4.3.

$$\frac{\partial p}{\partial z} = \frac{u}{k(z)} - \rho g \frac{\partial z}{\partial z} \tag{4.3}$$

The first term of the right side of Equation 4.3 represents the effect of viscous forces on the pressure variation caused by the friction between the fluid and the porous medium. While, the second term represents the hydrostatic pressure. Integrating Equation 4.3, it is obtained:

$$p = u \int_0^z \frac{\partial z}{k(z)} - \rho g \int_0^z \partial z + c \tag{4.4}$$

Due to the conservation of momentum and the conservation of mass, the fluid is incompressible, therefore, the velocity of the flow is considered constant and it is not integrated into Equation 4.4.

To determinate the value of the constant c, the initial conditions are analysed in Equation 4.4. So, the pressure is zero (atmospheric pressure) when the height of the liquid is zero as shown in Figure 4.4. When the height of the liquid is equal to the cane bed height (h), the pressure is equal to an unknown pressure (p_φ), which will be found through to experimental data.

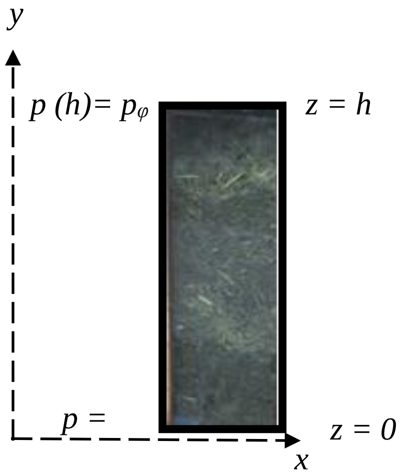


Figure 5.4 Initial conditions imposing to Equation 4.2

Source: Elaborated by the author

It was considered just the vertical flow in Figure 4.4, Note that the spatial coordinate system is right-hand-oriented with y-axis pointing upward; in this way, the permeability increases with the y-axis. Where, the variable *z* represents the liquid level at some reference point and not the position in which the pressure is measured.

Applying the initial condition, *p is zero* when *z* is zero, in Equation 4.4 it was determined that the integration constant (*c*) is equal to zero. In the same way, applying the initial condition, $p = p_\varphi$ when *z* is equal to *h*, in the Equation 4.3 it was obtained:

$$p_\varphi = u\int_0^h \frac{dz}{k(z)} - \int_0^h \rho g dz \tag{4.5}$$

Separating variables and integrating Equation 4.5:

$$u = \frac{\rho g h + p_\varphi}{\int_0^h \frac{dz}{k(z)}} \tag{4.6}$$

Substituting Equation 4.6 into Equation 4.4 it was obtained:

$$\frac{p(z)}{\rho g} = \frac{h + (P_\varphi/\rho g)}{\int_0^h \frac{dz}{k(z)}} \int_0^z \frac{dz}{k(z)} - z \tag{4.7}$$

The second term of the left side of Equation 4.7 represents the hydrostatic component, and the first term represents the permeability effect. The integral in the denominator represents the average permeability and the integral in the numerator represents the local permeability, it is associated with the terminal velocity.

4.4. Permeability variation through the cane bed

Permeability is a property of the medium, and it is the measure of the ability of a porous material (cane) to allow fluids to pass through it. The permeability of a medium is related to the porosity, but also to the shapes of the pores in the medium and their level of connectedness. In the case of the sugarcane, the permeability is inversely proportional to the compaction of the cane, and it is a function of the liquid holdup.

Assessing the permeability of the cane bed is a complex and challenging task that plays a key role to describe the variation of the percolation rate through the cane bed. The permeability evaluation is performed using experimental relationships of porosity-permeability. However, it does not work in the case of the sugarcane because the porosity is not constant due to its variety.

The permeability may vary through the diffuser due to the cane characteristics, index preparation and cane compaction. Lifting screws are used to unpack and regulate the permeability profile. So, immediately after lifting the screw, the cane bed could have regions of low permeability above regions of high permeability, there is a possibility of cavitation. However, a low permeability at the bottom is the natural tendency, and if it decreases monotonically, there is not cavitation. It can be concluded that void appears depending on the permeability variation through the cane bed, and it is not a locally determined phenomenon.

The pressure profile in the cane bed was determinate testing linear and exponential permeability functions in Equation 4.7. Thus, it was determined which permeability function allowed that the theoretical data matches with the experimental data. A quadratic permeability function was not considered because the permeability in the lower and upper part of the cane bed was different as shown experimental data.

4.5 Analysis of different permeability functions to determine the pressure profile

The liquid level on the manometer was recorded at the same time that the observed liquid level (*z*). It was measured based on observation at the sight glass installed at 50 cm from the manometers.

To compute the permeability profiles was considered than *z* varied from 0 m to 1.7 m with a variation interval of 0.1 m. while, the constants (η_1 and η_2) of the permeability function were adjusted to get an average permeability (K_m) of 0.005 m/s as shown in Table 4.1, as it was determined by Loubser and Jensen (2015).

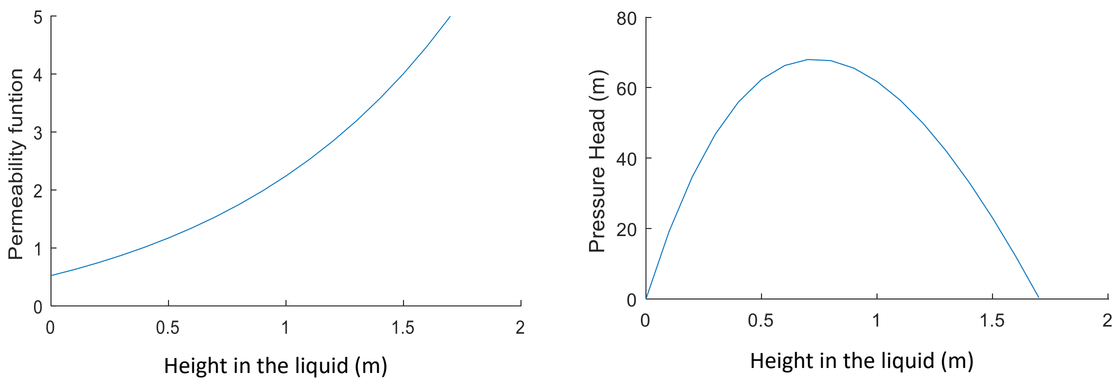
Table 5.1 Description of the parameters of the permeability function

Permeability Equation	**η_1**	**η_2**	**K_m (m/s)**
$k(z) = \eta_1 z+\eta_2$	50	300	0.005
$k(z) = \eta_1 z+\eta_2$	8	330	0.005
$k(z) = exp(\eta_1 z) +\eta_2$	1	-0.4778	0.0051

Source: Elaborated by the author

Due to the compaction of the cane the permeability is greater on the cane bed surface and lowers in the bottom of the diffuser as it is expected in Figure 4.5A, however the pressure decreases after 0.8 meters as shown in Figure 4.5B and there is not a physical reason to this variation.

Figure 5.5 From the left to the right, A. Exponential permeability function; B. Pressure distribution through the cane bed calculated using the exponential function of permeability

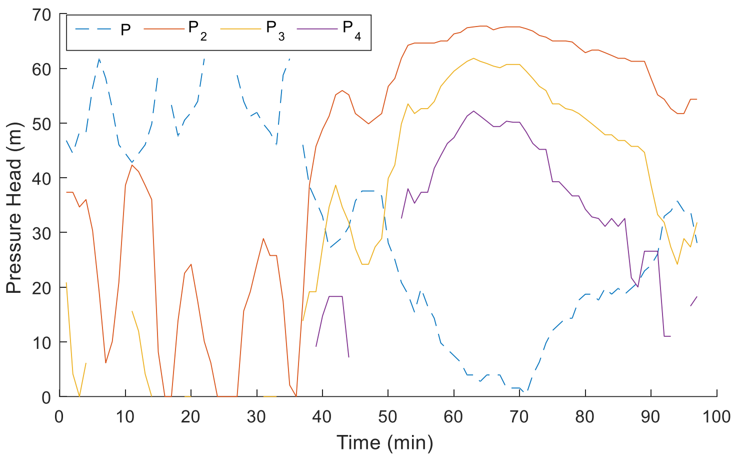


Source: Elaborated by the author

In addition, it is a wrong pressure profile since it distorts its natural variation of the pressure as shown by the experimental data in Figure 4.6. Then, the pressure profile should not have a negative slope, as shown by Rein and Ingham (1992).

Figure 4.7 represents the theoretical pressure calculated using the exponential function of the permeability, Where *P* is the pressure calculated using the measurements of the observed liquid level (Z_L) in Equation 4.7 and P_2, P_3, and P_4 are the pressures calculated using the liquid level measured in the manometers (Z_2, Z_3, Z_4), in Equation 4.7. Note, a water column with less than 1.7 meters cannot create the pressure shown in Figure 4.6.

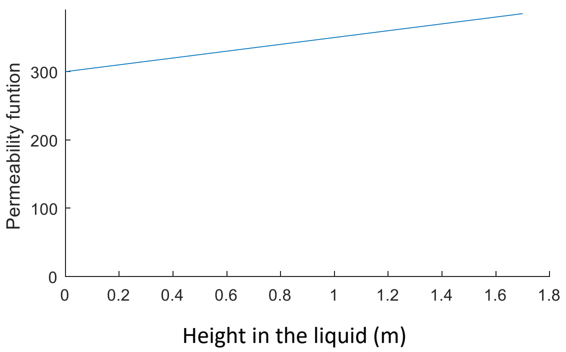
Figure 5.6 Theoretical pressure calculated using the exponential function of the permeability (shown in Figure 4.5) in Equation 4.7.

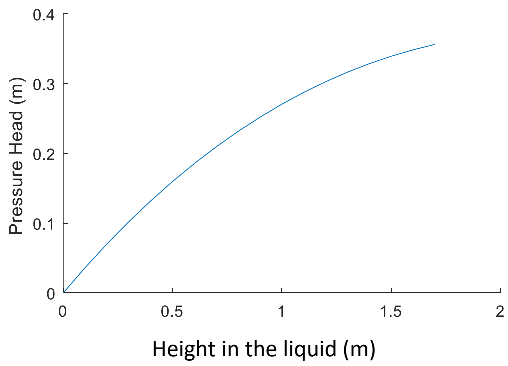


Source: Elaborated by the author

A linear function of permeability was used in Equation 4.7 to get Figure 4.7 and Figure 4.8, since an exponential permeability function not presentment satisfactory results.

Figure 5.7 From the left to the right, A. Linear permeability function; B. Pressure distribution through the



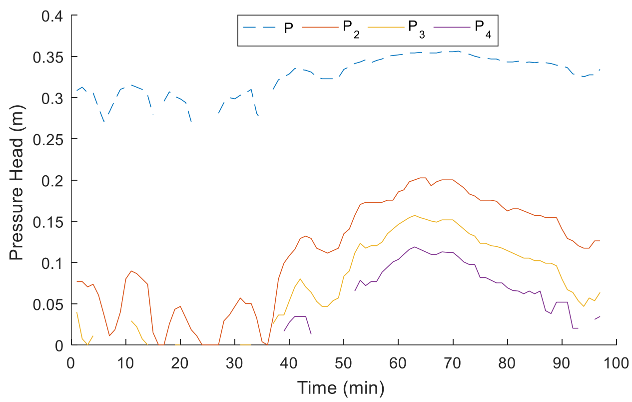


cane bed calculated using the linear function of permeability with constants $\eta_1 = 50$ and $\eta_2 = 300$

Source: Elaborated by the author

The observed liquid level creates a higher pressure (P) in Figure 4.8 because it represents the whole column of liquid. The manometric tube installed near to the surface of the cane bed present a lower pressure (P_4) than the others because they measured a smaller column of liquid, due to their location. The difference between the readings of each manometer may be due to cane compaction, friction effects and hydrostatic effects.

Figure 5.8. Theoretical pressure calculated using the linear function of the permeability (shown in Figure



4.7) in Equation 4.7

Source: Elaborated by the author

The linear function of permeability in Figure 4.7A permits that the pressure *P* matches with the pressure in all the manometers, as shown in Figure 4.8. However, the variation of pressure curve *P* is lower than the variation of the pressure curve P_2, P_3 and P_4, and these curves should be similar as shown the liquid levels in the manometers (Z_2, Z_3, Z_4) and the observed liquid level at the sigh glass (Z_L) in Figure 4.9. Therefore, a linear function with different constants will be tested.

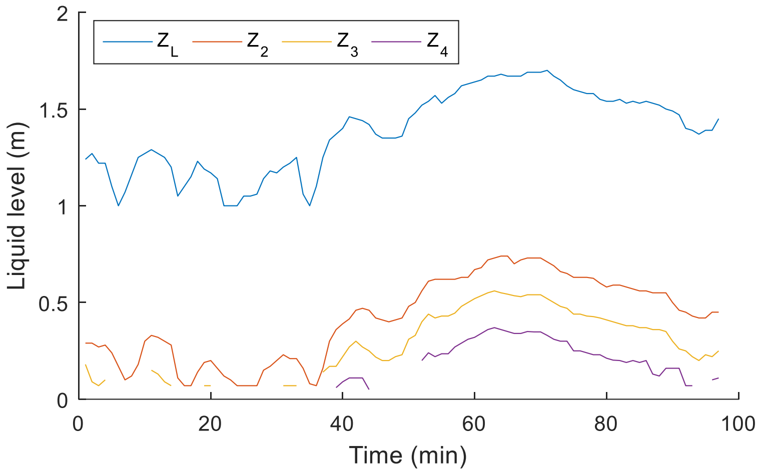
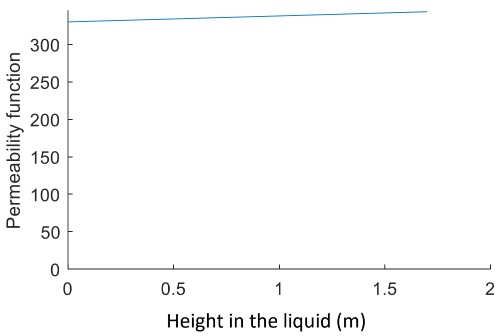


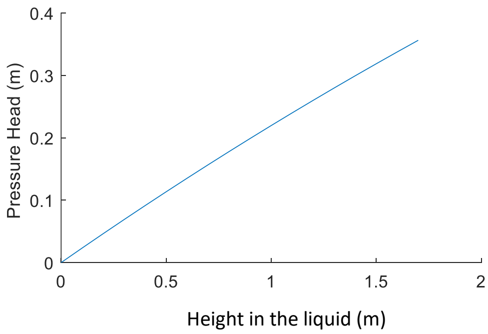
Figure 5.9 Comparison between observed liquid level and the liquid levels measured on the manometers

Source: Elaborated by the author

The experimental data helps to find the correct permeability function, so based on the previous results, it can be concluded that the pressure should vary linearly in order to keep the same fluctuation of the pressure curves, therefore a linear function of pressure will be calculated by the adjustment of constants from the linear function of permeability. In this way, the constant η_2 was adjusted to keep the value of the average permeability at desirable levels, since the constants associated with the permeability function could be changed as long as an average permeability of 0.005 m / s was maintained. Besides, the increase in the constant η1 in the permeability function increases the curvature of the pressure, as shown in Figure 4.7A and when it was calibrating the constant η1 in the simulations in the Matlab program. Therefore, it was reduced from 50 to 8 to obtain a linear pressure function as shown in Figure 4.10.

Figure 5.10 From the left to the right, A. Linear permeability function; B. Pressure distribution through the cane bed calculated using the linear function of permeability with constants $\eta_1 = 8$ and η_2



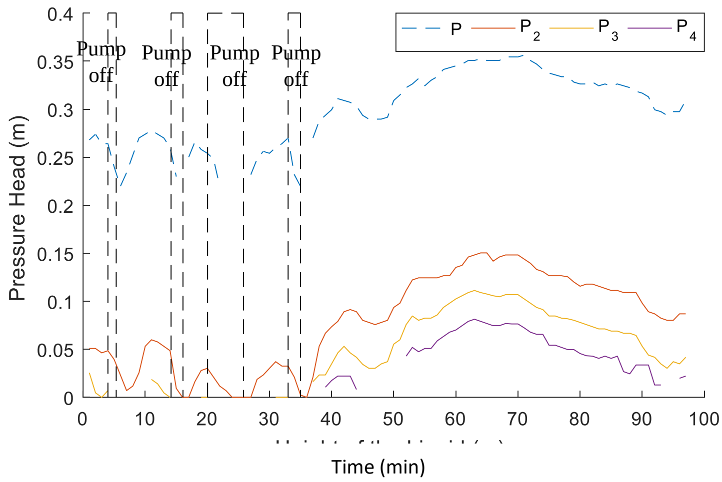


=344

Source: Elaborated by the author

To understand the variations of permeability on the juice distribution, the fourth pump was turned off at different time interval as shown in Figure 4.11 and Figure 4.12. This pump is responsible for spraying liquid on the top of the cane bed.

Figure 5.11 Theoretical pressure calculated using the linear function of the permeability (shown in Figure



10) in Equation 4.7

Source: Elaborated by the author

The pressure in Figure 4.11 was computed using the linear function of pressure showed in Table 4.1. The pressure decreases from the 70 minutes to 98 minutes even when the pump was operating normally but it is impossible to describe the reason of this variation because the diffuser is a black box where the variation of variables as compaction level, permeability, preparation index are unknown. In addition, due to the dimensions of the diffuser different cane varieties coming from several farms are fed the diffuser constantly.

4.6. Case 1 and Case 2

Case 1 (Figure 4.11) and case 2 (Figure 4.12) correspond to the variation of pressure when the liquid inside of the cane bed is being drained by deactivation of the pump fourth.

The pressure decreases when the pump is turned off and this effect is more pronounced in case 1 than in case 2 as shown in Figure 4.12.

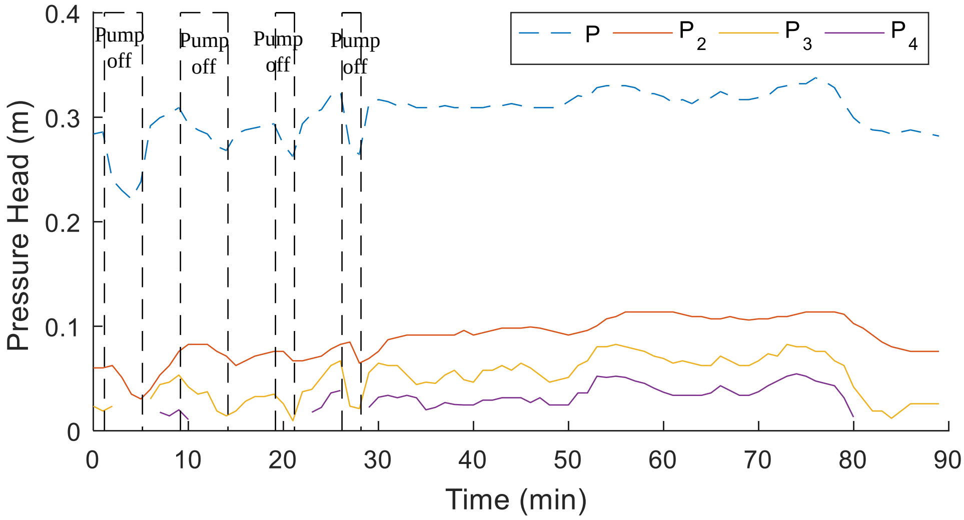


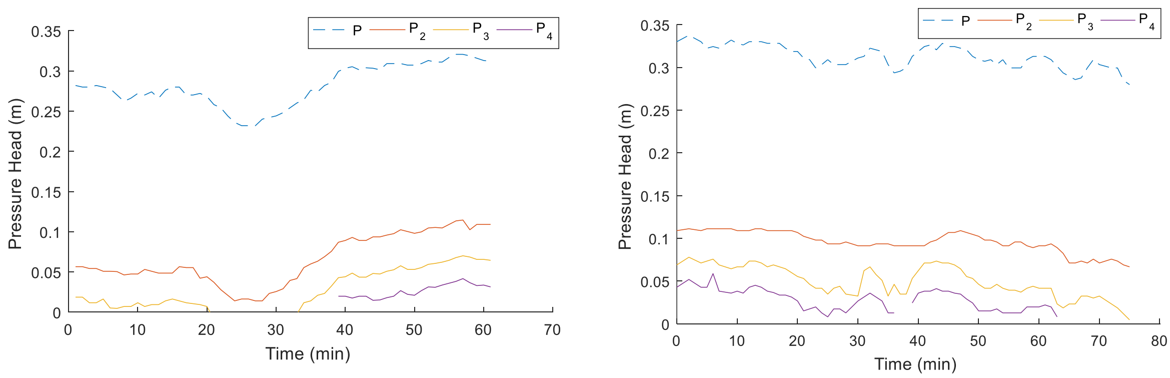
Figure 5.12 Variation of pressure caused by turning off and on the fourth pump for case 2

Source: Elaborated by the author

4.7. Case 3 and Case 4

Case 3 and case 4 correspond to the variation of pressure under normal operating conditions. Data of the liquid level on the manometers were recorded under normal operating conditions on different days during 60 minutes for case 3 and during 75 minutes for case 4 as shown Figure in 4.13.

Figure 5.13 From the left to the right, **A**. Variation of pressure in normal operating conditions for case 3; **B.** Variation of pressure in normal operating conditions for case 4



Source: Elaborated by the author

All the pressure curves presented in the previous graphs (Figure 4.11- 4.13) have similar fluctuations but they are dislocated to a certain value that it is called calibration parameter, which makes the pressures P_2, P_3 and P_4 adjust to the pressure P. it is important to determinate this parameter to control the liquid level through the diffuser and the automatization of the spray deflector position, responsible for distributing the liquid onto the bed surface, according to the settings selected.

The calibration parameters were calculated comparing the pressure P with the pressure of the three manometric tubes until to find the maximum Mean Square Error (MSE) between each other in Table 4.2. Where *Data* represents the number of samples recording per trial.

Table 5.2 Calibration parameters for the pressure curves

Figure	**Calibration parameters for P_2, P_3, P_4 (m)**								
	P_2	***MSE_2***	***$Data_2$***	***P_3***	***MSE_3***	***$Data_3$***	***P_4***	***MSE_4***	***$Data_4$***
Figure 4.11	0.217	0.94	97	0.255	0.96	75	0.28	0.975	50
Figure 4.12	0.215	0.5	90	0.256	0.87	87	0.28	0.92	62
Figure 4.13 A	0.217	0.6	72	0.262	0.81	72	0.29	0.83	58
Figure 4.13 B	0.216	0.94	61	0.26	0.94	54	0.28	0.96	23

Source: Elaborated by the author

The second manometric tube (M_2) record the largest number of measures due to its location but it has the lowest MSE, while the fourth manometric tube (M_4) record the smallest number of measures and it has the highest MSE in Table 4.2.

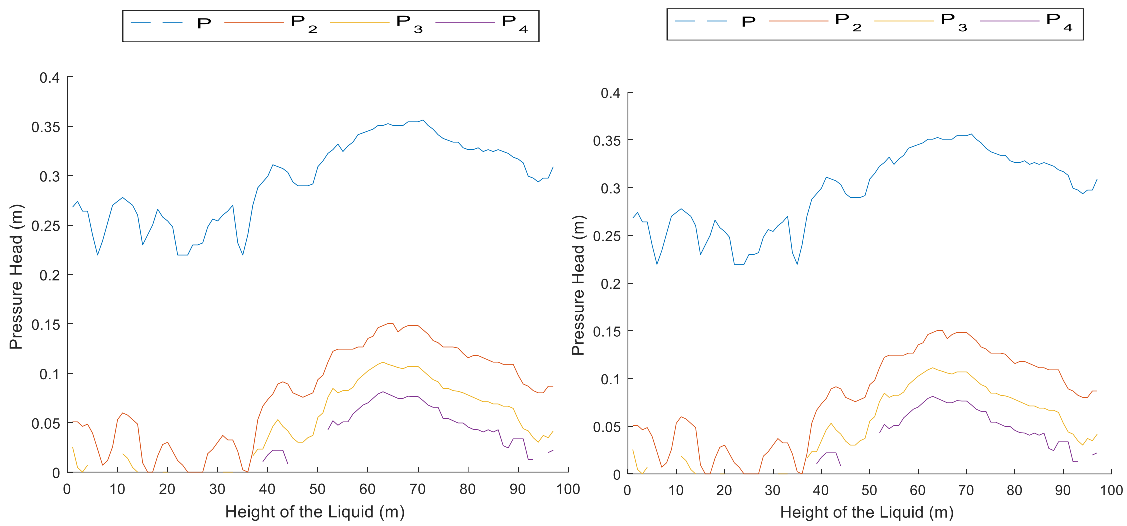
It is important consider that the third manometric tube and the second manometric tube recorded the same number of samples in the Figure 4.13A, however, the third manometric tube has a significantly higher MSE than the second manometric tube, a similar situation is presented in Figure 4.12 but the only difference is that the third manometric tube recorded 3 data less than the second manometric tube. It could happen because the permeability changes through the cane bed, it is higher in the surface, and therefore, the pressures near the bottom can change significantly in relation to the pressure generated by the observed liquid level. Finally, the calibration parameters for the pressure P_2, P_3 and P_4 tend to converge in almost all the cases.

Finally, the coefficient of variation (CV) is a measure of relative variability, and this statistical is the ratio of standard deviation divided by mean value, expressed as a percentage. The coefficient of variation of the calibration parameter for P_2, P_3, and P_4 are 0.4 %, 1.28 %, and 1.77 % respectively.

4.8. Effect of the cane bed height in the pressure distribution through the cane bed

The cane bed height varies constantly through time, and the pressure is slightly affect by the cane bed height as shown in Figure 4.14, therefore, a constant cane bed height could be used in the mathematical model.

Figure 5.14 From the left to the right, variation of pressure using *h* variable and using h constant (1.7 m)



Source: Elaborated by the author

4.8 Comparative analysis between different techniques used to monitor the observed liquid level in a cane diffuser bed

As mentioned above, two methods of indirect measurement of the liquid holdup have been studied therefore, a comparative analysis was used to assess these techniques of monitoring the liquid level, and furthermore, the advantages and the disadvantage of each method are presented in Table 4.3.

Table 5.3 Comparison between conductance and the liquid levels measured on the manometers as indirect measure of the observed liquid level

Parameter	Conductance	Pressure
Sample rate	Conductance measurements in a cane diffuser are simple and fast, they are very suitable for routine testing and long-term monitoring since they can be configured in different sample rates	The sampling rate is lower using the manometers than the conductivity meter since the data in the manometers were recorded manually.
Boundaries of the measurements	The distribution of the current through the cane bed is unknown, however, the boundaries of the conductance measurements are known since the conductivity meter is able to detect fluctuations between electrodes separated by three meters but it did not detect the conductance variations when the electrodes were separated by nine meters.	The liquid holdup is variable, so the manometers must be installed at least in three points in the two walls of the diffuser, however, these measurements could not determinate the variation of the pressure throughout the stage since the boundaries of pressure measurements are unknown and it is not possible to install a manometers in the middle of the stage

	As mentioned above, three electrodes, located at a distance of 3 meters from each other, can provide a measure of conductance through the whole diffuser's stage since the stage is 9 m wide.	
Detection of flooding	The conductivity meter is able to detect flooding in the cane bed without another type of measurement since when the cane bed has flooded the conductance of the three channels remain in specific values without any fluctuations. However, the main issue of this measurements system is a conductance value can coincide with two observed liquid levels, so the conductance of the cane bed should be associated with the juice conductivity and with the height of the cane bed.	The manometric tubes can detect the liquid level and the mathematical relationship between liquid level on the manometer and observed liquid level was established. However, they cannot detect flooding in the cane bed, without measurements of the height of the cane bed.
Correlation Coefficients	There is no mathematical relationship between conductance and observed liquid level, however, the correlation coefficient between these two variables vary from 0.7 to 0.8 in the experimental trials	The relationship between the observed liquid levels is established by Eq. 4.7 and the correlation coefficients between the observed liquid level and liquid level measured on the manometer varies from 0.876 to 1, as shown the different experimental trials.

Source: Elaborated by the author

Chapter 5

Electrical Impedance as a Possible Indicator of Sugar Concentration and Liquid Holdup in a Cane Diffuser: Evaluation on a Plant Scale and on a Laboratory Scale

5.1 Introduction

Sucrose is extracted from crushed and shredded cane by continuous washing of the cane bed with juice and imbibition water at 95° C, and by injection of steam water at 250 kPa in the Maidstone diffuser.

Diffusers utilise two sucrose extraction processes from prepared cane, namely (a) washing- sucrose is mechanically removed from the surface of the fibre using water and (b) diffusion- sucrose is transferred from the fibre cells (higher sucrose concentration) to the surrounding (lower sucrose concentration) extract (REIN, 2007).

The diffusers are used to reduce the velocity of the cane bed and increase the static pressure of the fluid passing through a cane bed. They are composed for a set of stages between 10 to 18 stages, and the number of stages depends on the crushing capacity. Every stage has a tray where the juice is deposited and a spray to distribute the liquid in the surface of the cane bed.

On another hand, high percolation rates of liquid promote the transfer of mass and contact between the liquid and the fibre. Percolation rate of juice varies in time and along of the diffuser, these variations are due to changes in the operating conditions and in the variety of the cane. Which may cause liquid to slow down, disperse sideways or speed up producing flooding and an uncontrolled mix of juice between the stages (LOUBSER & JENSEN, 2015).

Currently, there is no mechanism to measure and control the retention of liquids in a cane diffuser, inasmuch as, frequently, the flow meter cannot measure the liquid that percolates in each stage because it can be dispersed to other stages, or the flow meter measures the liquid that comes from other stages without percolating that particular stage. Therefore, the extraction of sucrose can be improved by the control and automation of the spray flap position, which is responsible for distributing the liquid onto the bed.

The impedance tomography (EIT) is the detection and exploration of differing electrical properties (capacitance, resistance, induction). The conductance can assess the permittivity distribution of dispersed materials in a fluid with a non-conductive continuous phase and the impedance can detect specific properties of materials (HOLDER, 2004).

The EIT is also used to monitor process reactions, monitor flow regimes, and concentrations, and provide data for on-line process control, as well as, imaging distribution, the determination, and control of flow characteristics.

In the electrical impedance tomography, the sensor is made from one or multiple electrodes in contact with the medium but not intrusive to the medium. An alternating current is applied to some electrodes and voltages are measured from the remaining electrodes, according to a predefined sensing strategy. Then these voltage measurements are used to reconstruct the impedance distribution within of the cane bed. The resulting signals are interpreted by a computer program to characterize the properties of the medium.

In this way, electrical impedance tomography methods are an interesting approach to this problem due to its simplicity and robustness. The electrical impedance of the medium can be influenced by the internal liquid level as well as by the conductivity of the extraction fluid. In this context, the resistive components result from the resistance to the passage of electrical current through the medium associated with observed liquid level as shown in the experimental results (ANGEL, *et al*., 2017; LOVE, 2017; LOUBSER, 2016). It is assumed that the sucrose concentration in the cane bed is associated with electrochemical reactions, in which electrons are exchanged in oxidation reactions. Thus, the main objective of this study was to assess experimentally capacitive and resistive effects in the Maidstone diffuser and on a laboratory scale. The impedance is assessed at laboratory scale because the capacitance and resistive affect differently the components of the overall impedance of the cane bed at different frequencies.

Finally, the mathematical model proposed is compared with the experimental data in order to find the constants of the equations which describe its behaviour as a function of time.

5.2 Methodology

The measurement method involves using direct current to apply an electrical signal into the system (cane bed - juice) and afterward, measuring the impedance to determine the mathematical function G(s), which could describe the behaviour of the dynamic liquid level and concentration of sucrose over time. The cane bed can be considered as a black box, as shown in Figure 5.1. The initial voltage is known and the variation of it through the cane bed is measured, thus it is possible to compute the impedance of the cane bed.

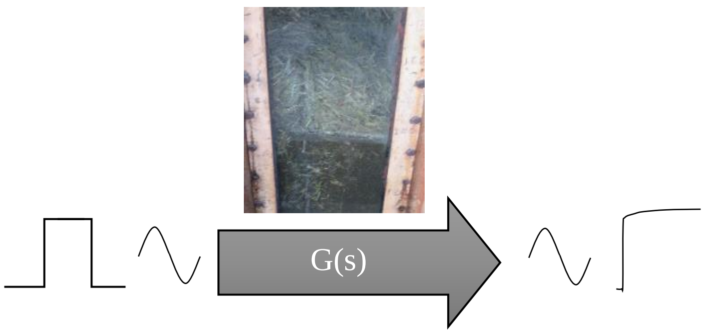


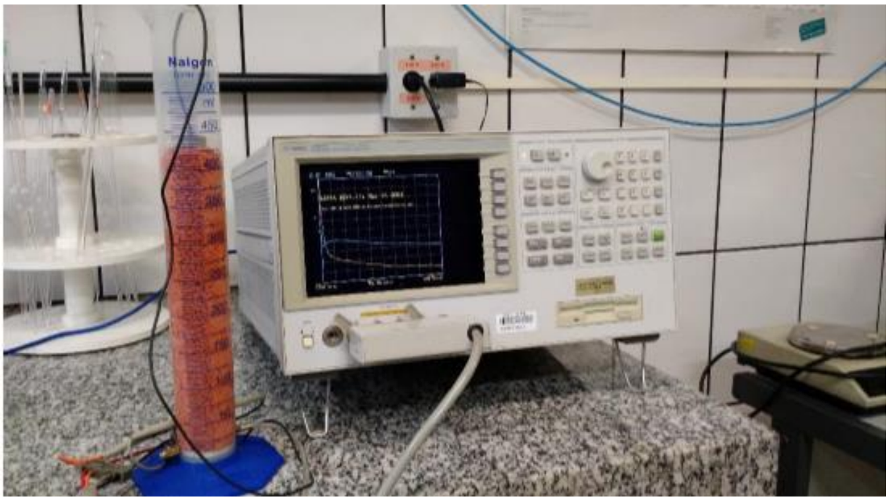
Figure 6.1. Signal analyses on the cane bed

Source: Elaborated by the author

Two types of electrical signals were used to measure the impedance of the cane bed: sinusoidal and the unit step signal. For a sinusoidal voltage input the polar form of the complex impedance relates the amplitude and phase of the voltage, and current. In particular: The magnitude of the complex impedance is the ratio of the voltage amplitude to the current amplitude; it could be associated with the liquid level. The phase of the complex impedance is the phase shift by which the current lags the voltage, it could be associated with the concentration of the sugar.

The set-up of the experimental trials conducted at laboratory scale to measure the capacitive effect with the impedance meter is shown in Figure 5.2, the characteristics of the experimental diffuser are described in section 5.3.

Figure 6.2 Measure of impedance through Agilent4294A Precision Impedance Analyser



Source: Elaborated by the author

To compute the magnitude and the phase of the impedance, it was used the method of least squares but the results obtained were not consistent, therefore, other advanced methods of signal analysis as the Truncated Singular Value Decomposition as proposed, by Brandi *et al*. (2014), can be tested.

Due to the mathematical complexity of finding the phase and the magnitude of the impedance, it was used a unit step voltage input of 5 volts to measure the impedance in the cane bed.

The constants of the differential equations which reduces the error between the experimental data and the theoretical data were found through the evolutionary experimental planning. It is an active statistical method: where a series of adjustments are made in the process, making changes in the inputs and observing the corresponding changes in the outputs. The advantage of this method is the easiness of identification of the order of the differential equations as shown in Figure 5.3.

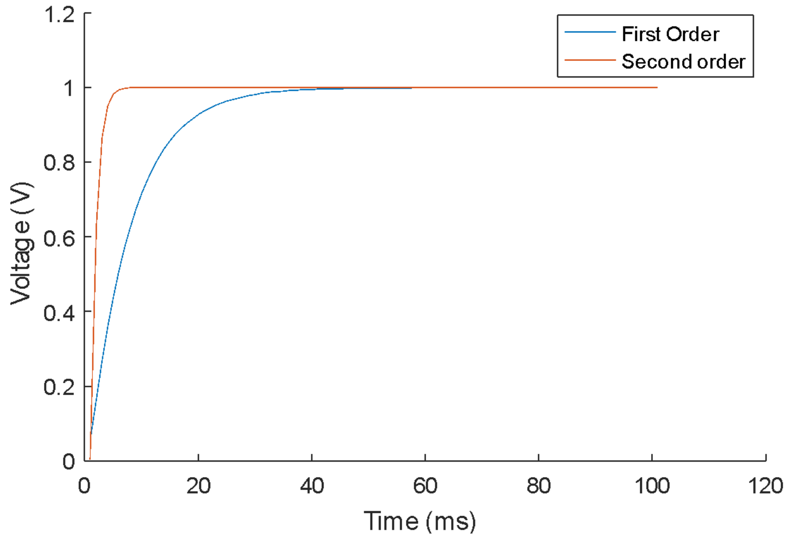


Figure 6.3 Comparison between differential equation of first order and second order

Source: Elaborated by the author

The data were filtered using the method of exponential smoothing and filter coefficients depends on the noise in the measurements in every experimental trial.

On another hand, the correlation coefficients between the main variables were computed. They determined the relationship between two variables and its variation interval is from -1 to 1, where -1 represents a direct, negative correlation, 0 represents no correlation, and 1 represents a direct, positive correlation. The appendix D shows how these coefficients were calculated.

Same conditions in the results mean that the cane bed was flooding and the data was recorded the same day at the same time with a different interval of one minute between every sample.

Characteristics of the liquid

The mixed juice brix varies from 9.5 % to 12 %, the pH from 5.2 - 5.3, the purity varies from 83.9 % to 86.5 % and the solids varies from 0.17 to 0.25. The density varies from 1036.8 to 1049.6 kg/m^3, it was calculate using the value of purity, and brix of the mixed juice in the web site of Jayes, 2018. In addition, the cane juice has inorganic components as Potassium, Sodium, Calcium, Magnesium, Iron, Aluminium, Copper, Zinc, Manganese, Cobalt, Silicon, Chloride, Phosphate and Sulphate.

Data validation

The liquid holdup is the liquid retain inside of the cane bed while the observed liquid level is the liquid observed at the sight glass. Then, the liquid level was used as indicator of the local liquid holdup since there is no other measure to evaluate this and because the liquid level is affected by the pump operation so, the liquid level decreases when the pump is turned off and it increases when the pump is turned on. However, the observed liquid level had not been used as a comparison variable for two reasons: the first is because the observed liquid level in the sight glass represent just a small area of the entire stage, but it is useful in this research because the third channel was installed at 3 m from the sight glass but the conductivity meter is able to detect fluctuation at this distance so, it assessed just the local liquid level in a small region of the diffuser. The second reason is that the wall effect is unknown; however, Angel *et al.*, (2017) show that this effect can be negligible.

Noise in the measurements

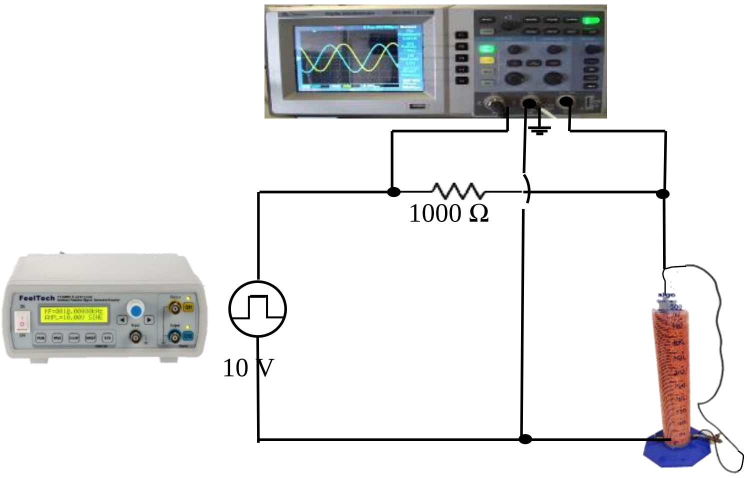
Noise in the measures is a critical issue of the impedance meter generated by parasitic currents, by unstable ungrounded earth connections, and by the change between the measurements of the voltage on the test resistors. Besides, the Arduino was not able to make a differential measurement, which filtered the noise; neither the NI USB 6009 from National Instrument is able to do that.

5.3 Laboratory Setup

The impedance of cane bed was assessed on a laboratory scale using cane juice, plastic particulate of regular form and a batch column diffuser, the column diameter is 0.045 meters and 0.5 meters high. The electrode diameter is 0.025 m.

The measurement method involved the use of an oscilloscope TDS 2014 (described in the Appendix E) to measure the voltage, and a functional signal generator MFG 4202 (described in the Appendix F) which was set up at different ranges of frequency. The input voltage was 10 volts as shown in Figure 5.4. The data were recorded manually.

Figure 6.4 Electrical circuit to measure the impedance on a laboratory scale



Source: Elaborated by the author

5.4 Plant Setup

As previously mentioned, the sinusoidal input voltage was not used due to the mathematical complexity of finding the impedance components, therefore a unit step signal was used. This method was used to evaluate the system electrochemical dynamics, which was described by a second-order transfer function. The initial voltage was zero and the final was 5V. A current probe resistor was placed in series with the system to determine its impedance according to with the Ohm Law of current.

The disadvantage of the unit step method is that the direct current produces a disassociation of electrons which promotes a chemical reaction. In the same way, high electricity or high frequency can produce electrolyze or dissociation of electrons.

The equipment used in the tests carried out in the laboratory could not be used in the Maidstone diffuser because the data were recorded manually and the impedance measurements were not made simultaneously with the three test resistances since it was not necessary because the tests were performed in the steady state. Therefore, a novel impedance measurement system of the cane bed was designed and built with an adjustable measuring interval, where the data acquisition is provided. A program was created on the LabVIEW platform which calculates the impedance of the cane mattress and changes sampling time and sampling number. The Impedance meter provides an accurate capability of the repeatable impedance measurement on a laboratory scale.

The impedance meter was composed of an open collector comparator LM339, three test resistors of 545 ohms, 1000 ohms and 9200 ohms, an Arduino platform and a data logging NI USB 6009 from the NATIONAL INSTRUMENTS. The appendix G gives more information about components of the equipment and the electrical circuit of the impedance meter is shown in Figure 5.5.

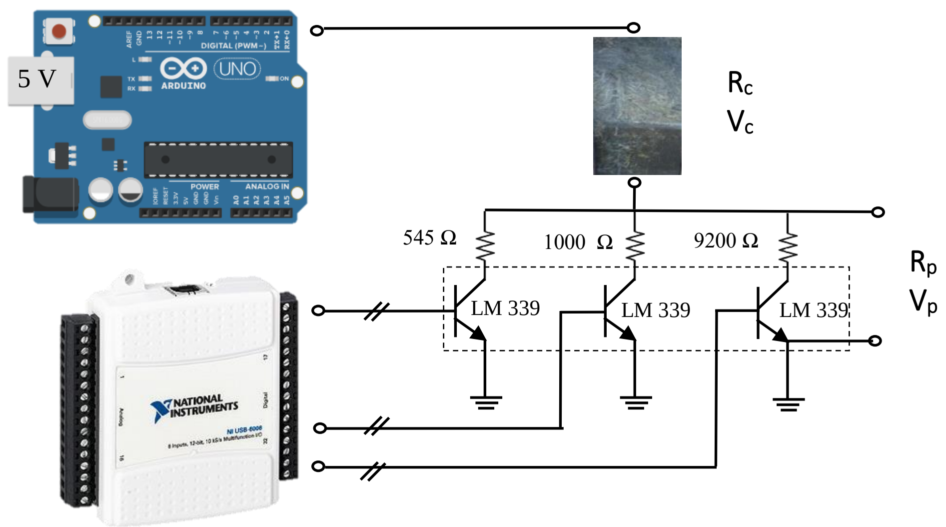


Figure 6.5 A simplified electric circuit of the impedance meter

Source: Elaborated by the author

The Arduino was used the voltage driver commanded by the NI USB 6009 from NATIONAL INSTRUMENT, which was used to record the voltage data, to alternate the test resistors and to measure the voltage in each one. In addition, a computational program was written on the program LabVIEW to calculate the impedance, configure the sample rate and the sampling time.

The cables of the impedance meter connected to the diffuser present a resistance of 0.5 ohms so they had no influence in the measurements.

In Figure 5.5 R_p is the test resistor, they were used to compute the value of the impedance of the cane bed, as shown in Eq. 5.1 and in Eq. 5.2. They were also used to avoid the noise in the measurements and the influence of others electrical equipment. The interval of variation of the cane bed impedance is unknown, therefore, three probe resistances of 1000 Ohms, 9200 Ohms, and 545 Ohms were used to compute the impedance of the cane bed. The accuracy of these results depends on the linear difference between the test resistors (R_p) and resistance of the cane bed (R_c), which represents the impedance of the cane bed, then the closer the impedances are the greater the accuracy.

The voltage was measured on the three test resistors (v_p) and on resistance of the cane bed (v_c) as shown in Figure 5.5. The output voltage (v_{fin}) was computed as the difference between 5 voltages and the voltage measured on the cane bed. So, the current on the test resistors (i_p) was computed through Ohm's law, thus, the current on the test resistors is:

$$i_p = \frac{v_p}{R_p} \tag{5.1}$$

Using Equation 5.1 the impedance on the cane bed is computed as:

$$Z_c = \frac{v_{fin}}{i_p} \tag{5.2}$$

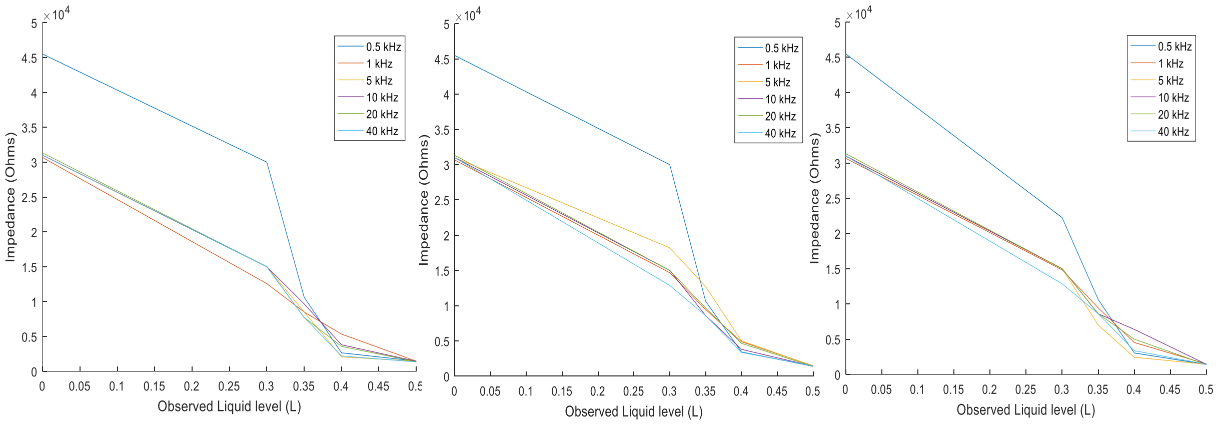
The sample rate was two samples per minute for all the results presented in this section, considering that for each voltage curve 100 data were recorded (samples per curve).

5.5 Results of the test performed on a laboratory scale: Variation of impedance at different frequencies

The results performed at laboratory scale showed that when the signal generator is used to apply a square wave to the sugarcane juice and plastic-liquid particle system the resistance in the cane bed decreases while the level of the cane juice increases because the cane juice has inorganic components, which facilitates the passage of the electrical current. This result is reproducible even when the impedance is evaluated at different frequencies.

The impedance of plastic particle and sugarcane juice was assessed as a function of the liquid level in an experimental diffuser at different frequencies as is show Figure 5.6.

Figure 6.6 Impedance variations of the system sugarcane juice and plastics particles at different



frequencies, the data were recorded three times under the same conditions

Source: Elaborated by the author

The data were collected three times under the same conditions for every experiment as shown in Figure 5.6, considering five sugarcane juice levels (0, 0.3, 0.35, 0.4, 0.45 L)

The analysis of the results show that the impedance is higher when it is evaluated at a frequency of 500 Hz, however, no pattern of variation was found when the impedance is evaluated at other frequencies.

The voltage curve of the system show in Figure 5.6 can be modelled as a second-order transfer function homogeneous with constant coefficients (OGATA, 2000), as shown in Figure 5.7.

$$G(s) = \frac{{\omega_0}^2}{s^2 + 2\zeta s + {\omega_0}^2} \tag{5.3}$$

Where ω_0 is called the natural frequency no damped; ζ is the damping factor, and the solution to this equation is:

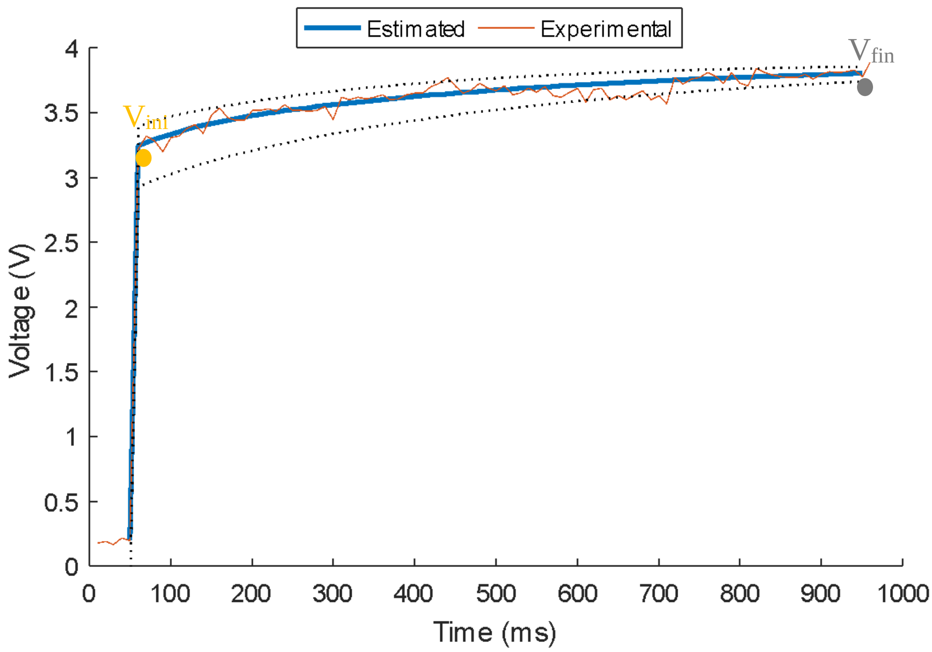
$$y(t) = y(\infty) - k_1 e^{-t/\tau_1} + k_2 e^{-t/\tau_2} \tag{5.4}$$

Where y (∞) is voltage in $t = \infty$; τ_1 and τ_2 are constant of time, k_1 and k_2 are real and distinct constants. It is an overdamped system. These constants were not found in a laboratory scale due to the characteristics of the column diffuser and because the tests were performed in the steady state.

The constants of the solution (Eq. 5.4) were found using the method of single search in a closed range and using the experimental data as a comparison variable. To achieve it a program in Matlab was written, it is described in Appendix H. This program was also used to calculate the output voltage as a function of time.

The mathematical model presented previously determined the estimated voltage variation (output voltage), with confidence interval of 95 % as the black dotted lines indicate in Figure 5.7, where the red line represents the experimental voltage. No filter was used to reduce the noise in the measures in Figure 5.7, 5.8 and 5.11.

Figure 6.7 The voltage response of the plastic-liquid particle system to a square wave signal, experimental and estimated output voltage



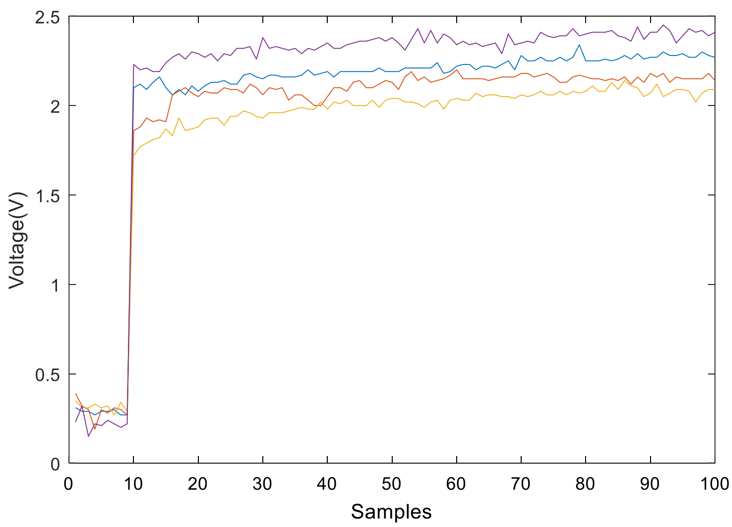
Source: Elaborated by the author

The variation of the values subsequent of V_{ini} represents the capacitive effect of the cane bed and V_{fin} represents the resistive effect of the cane bed. Therefore, if V_{ini} is equal to V_{fin} there is not capacitive effect.

5.6 Results of the test performed on a plant scale

The data presented in this section were recorded with the impedance meter and the aim of these experiments is to determine and to characterize the capacitive effect in the cane bed to achieve that the mathematical model presented above is used since the capacitive effect could be related to the flooding in the cane bed. Nevertheless, this hypothesis was not verified because all the data in Figure 5.8 were recorded the same day, under the same operating conditions and when the cane bed was flooded, with a sample rate of one minute. However, none of the constants of the voltage curves converge, as shown in Table 5.1, not even with the same values of observed liquid levels and cane bed heights.

Figure 6.8 Variation of voltage on the cane bed for different samples when the cane bed was in flooding,



therefore, observed liquid level and the cane bed were the same (1.76 m)

Source: Elaborated by the author

The test resistance of 9200 ohms was considered in the measurements of the voltage of the cane bed in Figure 5.8 and the sample rate was two samples per minute for all the results presented in this section, considering that for each voltage curve 100 data were recorded (samples per curve).

Table 5.1 shows that the constant coefficient related to the voltage curve do not converge, neither for the input nor for the output voltage of the curves when the cane bed was flooded. This is confirmed in Appendix I, where the same data as in Table 5.1 were recorded on different days. Accordingly, the capacitive effect is random and depends on unknown factors. This fact is support for the variation constants for each voltage curve.

Table 6.1 Constants of the voltage curves when the cane bed is in flooding

τ_1	τ_2	k_1	k_2	*W&Z* (m)	V_{fin} (V)	V_{ini} (V)
2.933333	7.186667	0.0246	0.140833	1.47	3.05	3.56
0.875	0.987793	0.172508	2.494372	1.48	2.75	2.96
5.377778	5.875463	0.014025	0.110741	1.50	1.5	2.03
13.56667	3.833333	0.0161	0.012333	1.71	1.85	2.07
11.91667	3.3	0.028417	0.25	1.75	2.06	2.08
25.9	10.625	0.008433	0.003333	1.75	2.23	2.41
290.0625	0.018333	0.245039	0.000422	1.76	2.09	2.02
290.0625	0.018333	0.245039	0.000422	1.76	1.91	1.73
27.80556	0.008438	0.008882	0.000844	1.76	2.1	2.27
12.43611	0.078222	0.027728	0.814	1.76	1.91	2.25
14.97222	3.294271	0.014352	0.059766	1.77	1.86	2.14
24.5	0.478125	0.013417	0.047813	1.77	1.72	2.09

Source: Elaborated by the author

Where, W is cane bed height (m) and Z is observed liquid level (m). The impedance was not assessed at different frequencies because there is no relationship between the capacitive effect and cane bed flooded, Consequently, the resistive effect will be assessed, which is related to the variation of the output voltage as shown in Figure 5.9. The filter coefficient is 2 in the data presented in Figure 5.9 and 5.11 – 5.13.

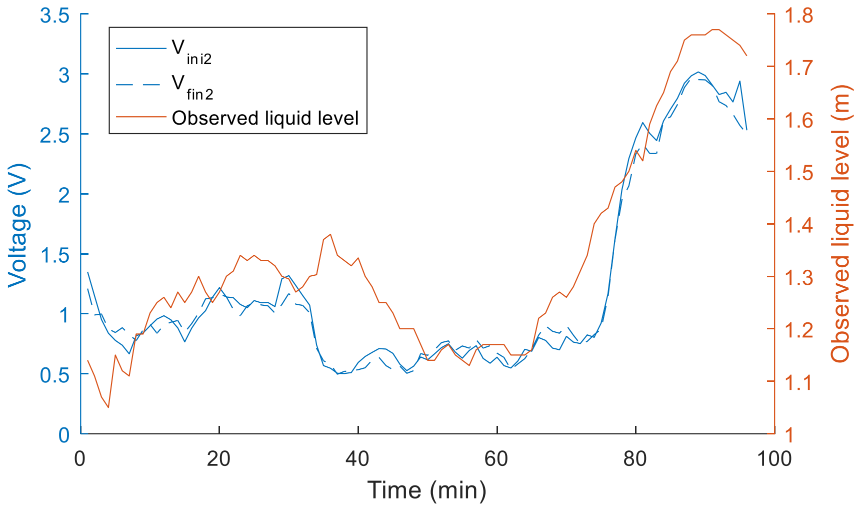


Figure 6.9. Variation of the input voltage, the output in the cane bed and the observed liquid level

Source: Elaborated by the author

Where V_{fin2} is is the output voltage of the cane bed (V) considering the test resistor of 9200 ohms (R_2) and V_{ini2} is the input voltage of the cane bed (V) considering the same resistor.

Note, the input and the output voltages have a similar variation of the observed liquid level in Figure 5.9. As shown the correlation coefficient of Table 5.2.

The voltage difference between the voltages ($V_d = V_{fin2} - V_{ini2}$) was compared with the observed liquid level in Figure 5.10 and there is no correlation between V_d and Z because the correlation coefficient is 0.14 as shown in Table 5.2. The mean value of V_d is 0.23 V, it means that although there is a capacitive effect this is not relevant considering the voltage of the cane bed varies from 0.5 to 3.5 V.

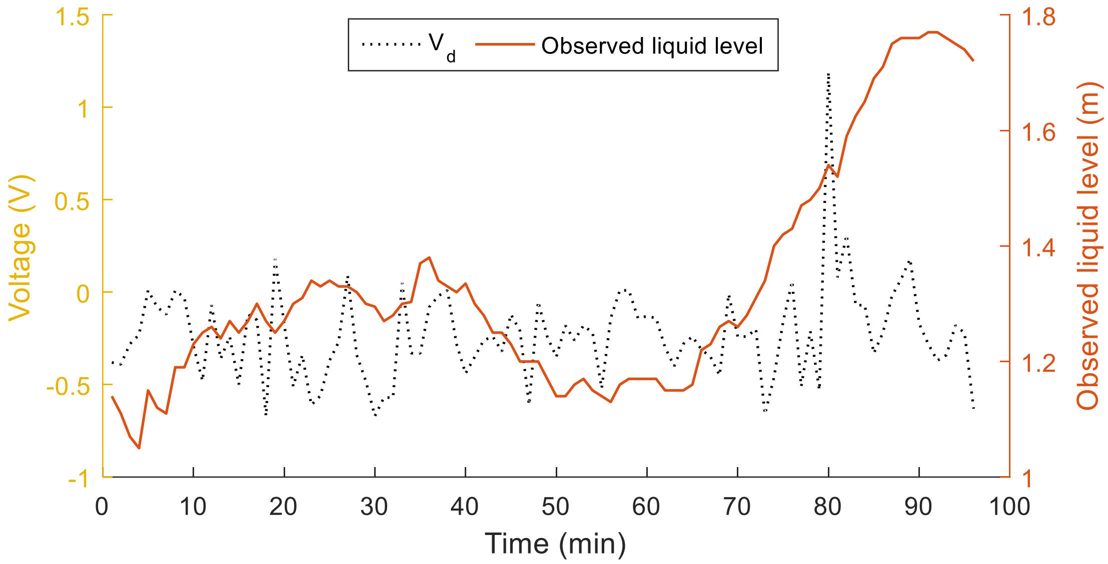


Figure 6.10. Comparison between V_d and the observed liquid level

Source: Elaborated by the author

The voltage measured on the test resistor and the voltage measured in the cane bed is shown in Figure 5.11. V_p and V_{fin} have the same variation with significantly different values. The numbers 1, 2 and 3 in the variables Vp and V_{fin} represent the resistor of 1000 ohms, 9200 ohms, and 545 ohms respectively. The variations between the voltage curves measured in the cane bed are less than the variations in the voltage measured in the test resistors.

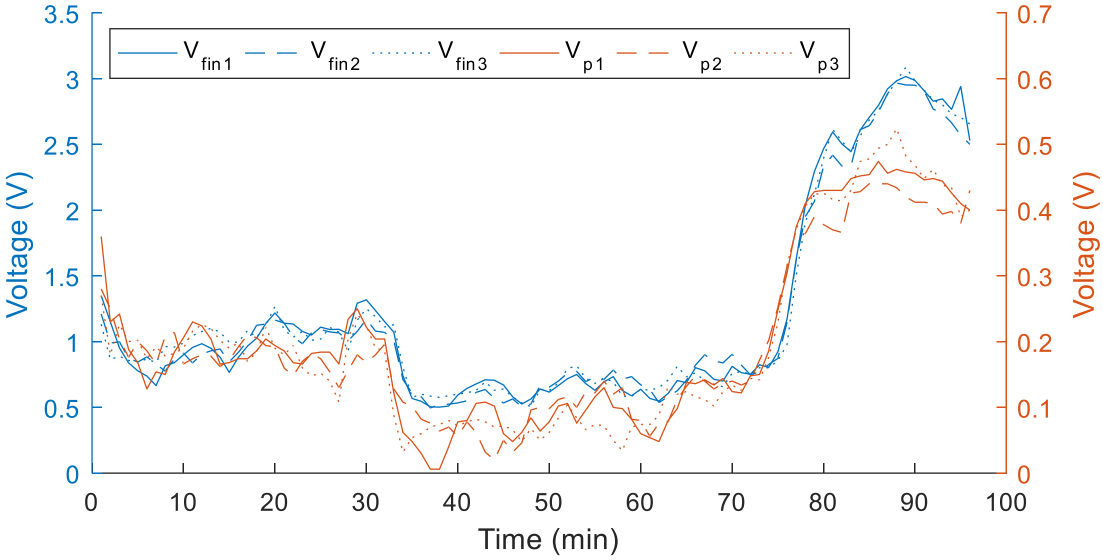
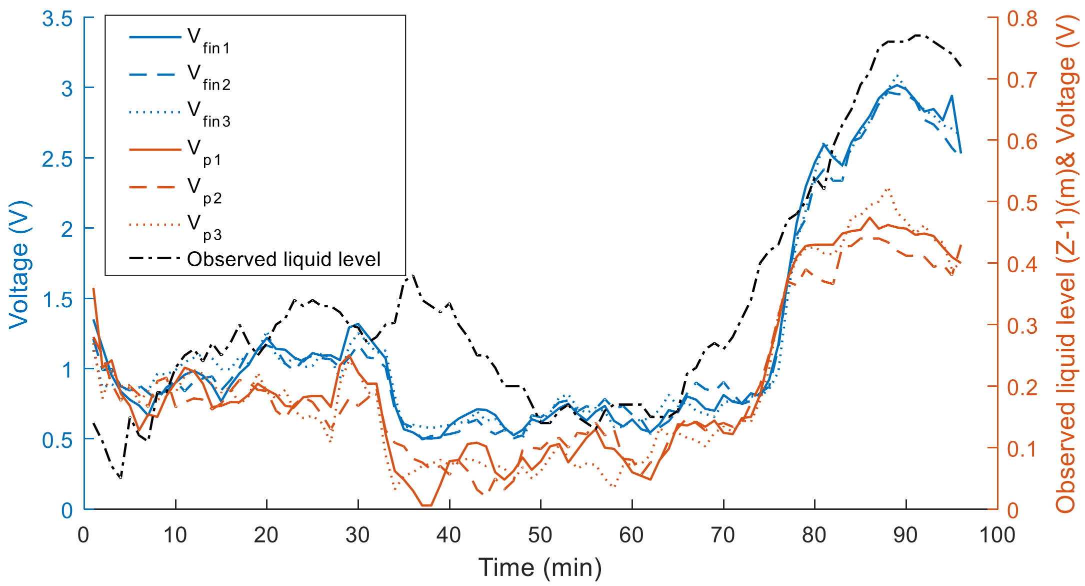


Figure 6.11 The output voltage measured on the cane bed and voltage measured on the test resistors

Source: Elaborated by the author

The measured voltage in the cane bed and the measured voltage in the test resistor follow the fluctuation of the observed liquid level, as shown in Figure 5.12. Withal, V_{fin} has a stronger relationship with the observed liquid level than V_p, as shown in Table 5.2.

Figure 6.12 Comparison between the voltage measure in the cane bed, the voltage measure in the test



resistors and the observed liquid level

Source: Elaborated by the author

The impedance of the cane bed was calculated using Eq. 5.2, and subsequently it was compared with the observed liquid level, as shown in Figure 5.13.

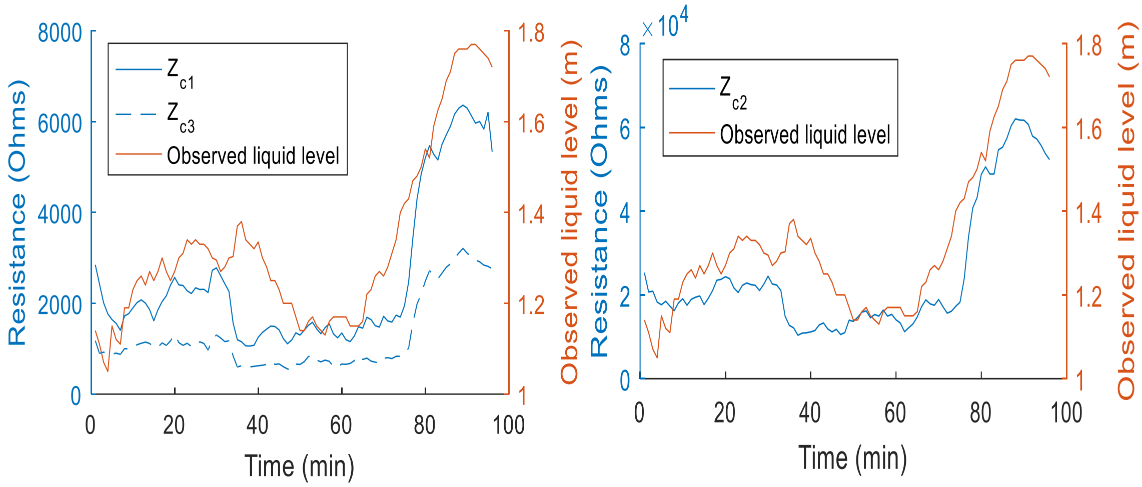


Figure 6.13 Impedance in the cane bed and the observed liquid level

Source: Elaborated by the author

Where Z_{c1} , Z_{c2}, Z_{c3} is the Impedance on the cane bed (ohms), considering the test resistor of 1000 Ohms, 9200 ohms and 545 ohms respectively.

Although the impedance of the cane bed follows the fluctuations of the observed liquid level, the highest impedance corresponds to the measurements recorded with the resistor test of 9200 ohms, because it is proportional to the impedance as shown Eq. 5.1 and Eq. 5.2. In addition, the order of magnitude of the variable impedance could not be generated by the thermal and chemical process produced in the cane bed because the impedance was too high.

Rc_1 has the greatest correlation coefficient and Rc_3 the lowest correlation coefficient as shown in Table 5.2. So as to the correlation coefficient is a measure of the linear dependence between two variables.

Table 6.2 Correlation coefficients for the variables in Figures 5.9 – 5.13

Variables	Correlation coefficient
Z and V_{ini2}	0.91
V_{ini2} and V_{fin2}	0.95
Z and V_d	0.14
Z and V_{fin1}	0.91
Z and V_{fin2}	0.91
Z and V_{fin3}	0.91
Z and V_{p1}	0.82
Z and V_{p2}	0.83
Z and V_{p3}	0.84

V_{fin1} and V_{p1}	0.81
V_{fin2} and V_{p2}	0.75
V_{fin3} and V_{p3}	0.76
Z and R_{c1}	0.912
Z and R_{c2}	0.906
Z and R_{c3}	0.89

Source: Elaborated by the author

Chapter 6

Conclusions

This study has resulted in the development of different techniques to monitor the liquid level through indirect measurement of conductance, pressure and electrical impedance. To achieve that, mathematical models of characteristics of the percolating liquid in the cane bed were developed. This can be used to adjust and control the spray position responsible for distributing the juice at the top of the sugarcane bed.

The achievement of this research has involved a detailed study of liquid level measurement techniques, which influences extraction performance. This chapter summarizes the main conclusions of the study;

6.1 Chapter 2: Review of previous work

The main results between the comparison of mill tandem and diffuser of this work can be thus summarized:

- Capital and maintenance cost comparisons show the major advantage of diffusion in relative to milling.
- In terms of energy consumption: mill tandem consume more electrical energy than diffusers, however, diffusers consume more thermal energy than the mill tandem.
- The diffuser presents lower capital and operating costs than the mill tandem.

- The diffuser has the ability to achieve higher sucrose extraction than the mill tandem.
- The use of mills is more profitable than the use of diffusers in aspects such as the reliability and the pre-processing of the cane, because the diffusers are more sensitive to the interruptions and require greatest cane preparation than the mills tandem. This is achieved through a heavy duty shredder, and steady operation incorporating adequate temperature control.
- The diffuser evidences some disadvantages as higher content of sand and moisture in the bagasse and colour in juice.
- Due to the long residence time of the cane in the diffuser, start-up and liquidation operations are more prolonged with a diffuser.
- The diffuser needs less supervision and number of operators.

6.2 Chapter 3: Monitoring juice hold - up in a cane diffuser bed using electrical conductivity - Evaluation on a plant scale

The correlation coefficients demonstrate that the average conductance and the conductance of the third channel have a stronger relationship with the observed liquid level than with the flow rate.

The problems of this measurements system are the average conductance of the cane bed can be altered by the formation of liquid deposits in one of the channels and a conductance value can coincide with two liquid levels, so the conductance should be associated with the juice conductivity and with the height of the cane bed.

The flow rate is not affected by the variation of the spray flap position contrary what happens with the conductance and there is no a linear relationship between observed liquid level and the flow rate, as well as, between the flow rate and the conductance in normal operating conditions. However, the conductance and the flow rate have a similar variations with the observed liquid level on special conditions, such as, when the diffuser is fed with sugarcane, when the recirculation pumps 2 - 4 are deactivate and when the diffuser stops to operate.

The correlation coefficient show that the cane bed height has no relationship with any variable (conductance, flow rate, and observed liquid level).

Finally, it was concluded from the analysis if the results that it is necessary install several conductivity meters and a few cane height meters along of the diffuser.

6.3 Chapter 4: Pressure distribution in a porous medium as indicator of the observed liquid level

The analysis of the results showed that the pressure profile is altered by the permeability functions and the experimental data converge with theoretical data through the calibration of the constants of a permeability linear function.

A mathematical model was created to find the relationship between the pressure and the observed liquid level. In addition, the calibration parameters which permits fit the pressured on the manometers with the pressure caused by the observed liquid level height was found it and the variation coefficient is less than 2% for all calibration parameters.

The effect of the height of the cane on the variation of the liquid level on the manometer is negligible, so a constant value of the cane bed height can be used in the mathematical model.

The correlation coefficients show a strong relationship between the observed liquid level and pressure. Reproducibility tests have confirmed these results.

6.4 Chapter 5: Electrical Impedance as a Possible Indicator of Sugar Concentration and Liquid Holdup in a Cane Diffuser: Evaluation on a Plant Scale and on a Laboratory Scale

The results on a plant scale show the capacitive effect is random and cannot be associated with any specific characteristic of the extraction process of sucrose. The capacitive effect is also not related to the flooding of the cane bed, since the tension curves of the flooded cane bed have no similarity between them, although the data were collected under the same conditions.

In addition, the capacitive effect is not significant since the input voltage curve and the output voltage curve measured on the cane bed vary slightly. Due to the aforementioned, the impedance was not assessed at different frequencies on a plant scale.

The resistive effect is associated with the level of liquid observed as shown by the input voltage and the output voltage measured in the cane bed.

The correlation coefficients show a strong relationship between the voltage and the impedance measured in the cane bed with the observed liquid level.

The Impedance meter can detect the observed liquid level. However, they cannot detect flooding in the cane bed, without another measurement as the cane bed height.

The physical phenomenon can be modelled through a transfer function of the second order, in which the parameters can be associated with constant coefficients which represent an RC equivalent circuit. Where the mathematical model proposed determined with high accuracy the variation of the output voltage with a confidence interval of 95 %.

6.5 Comparative analysis between different techniques used to monitor the liquid level in a cane diffuser bed

A comparative analysis was used to assess the different techniques of monitoring the liquid holdup; furthermore, the advantages and disadvantages of each method are presented.

The method of using electrical impedance as a possible indicator of the liquid level in a cane diffuser was not assessed in this analysis because of the capacitive effect in the cane bed is negligible and the resistive effect is evaluated by the conductivity meter

6.6 Contributions of this research

- Designed and ensemble of an new industrial impedance meter

- Creation of new methodologies to monitor the liquid level in a sugarcane diffuser
- Conducted experimental trials of conductance on a plant scale
- Conducted experimental trials of impedance on a plant scale and on laboratory scale
- Development of mathematical models to find relationship between the different variables such as, impedance, pressure and conductance and observed liquid level
- Development of a program in Matlab to record the voltage data from the impedance meter.
- Carrying out simulations in Matlab to validate the experimental data with the theoretical models.

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GLOSSARY

Liquidation: At the time of short (<24 h) scheduled shutdowns multi-tray clarifiers are generally left full. In order to reduce the inversion losses in the hot juice, it is good practice to raise the pH set point and to lower the clarifier rnud levels for some hours before shutting down. Even so, the inversion losses are quite significant (the estimated loss at 96 C, 7.2 pH, in 24 h storage time is 2.1 % and the colour of the stored juice increases appreciably (the estimated increase in juice colour for the above storage conditions is 20 %. Full liquidations can only be carried out several times in each season during extended stops. During the liquidation periods a thorough internal cleaning can be carried out and essential maintenance of mud pumps and full drives can be scheduled. Because of the relatively low juice volumes held in SRI and SRT clarifiers full liquidation of these clarifier types can be made in shorter scheduled stops with much less disruption to the process. Maintenance and cleanliness can then be scheduled more regularly, and sugar inversion losses and colour problems during storage can largely be avoided.

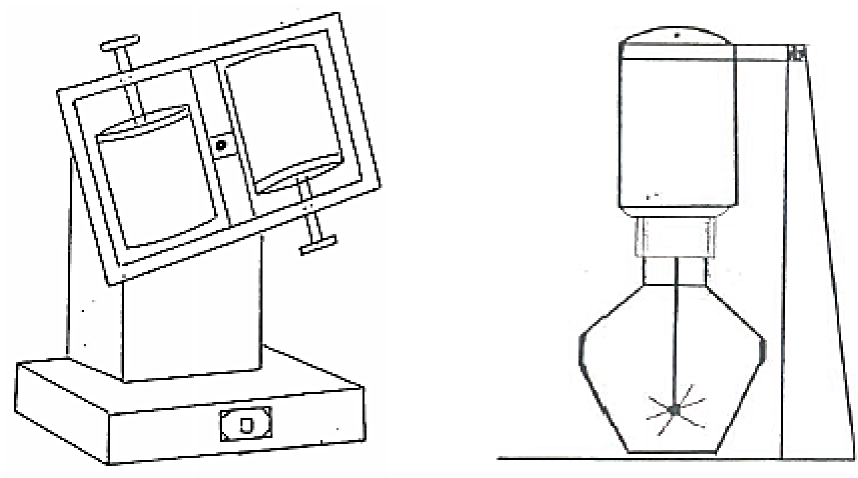
Brix is the percentage in the mass of soluble solids contained in a chemically pure sucrose solution. It is determined in a digital refractometer with automatic temperature correction.

APPENDIX A: Preparation Index (PI)

Equipment

- Semi-analytical balance, with a maximum resolution of 0.1 g
- Apparatus for determining the Preparation Rate (see Fig. 1), with a speed of 60 ± 5 rpm
- Extractor, South African type (Fig. 2)
- Automatic Digital Saccharimeter

Figure 1. From left to right; Apparatus for determining the preparation index and Extractor, South African type



Source: Cosecana (2006)

Process

- To disintegrate sample of cane obtained in horizontal or oblique sampling probe in the equipment to be evaluated
- Homogenize the disintegrated sample
- Transfer 500g of this sample to the extractor recipient;
- Add 2000 ml of distilled water;
- Turn on the extractor and keep it in shake mode for 15 minutes in the case of sharp blades;
- Cool and filter the extract obtained in a rotary filter funnel or in cotton;

- Clarify with a clarifying aluminum-based mixture a 200 ml aliquot of the filtered extract and carry out the saccharimetric reading, obtaining the reading "zero" (Lo);
- Transfer to the containers of the PI apparatus two 500 g samples of the same sample prepared and homogenised;
- Add to each vessel 2000 ml of distilled water, connect and keep the apparatus agitated mode for 15 minutes;
- Clarify, with aluminum-based clarifier, aliquots of 200 ml of the two containers of the apparatus;
- Carry out the saccharimetric readings of the clarified aliquots and calculate the average reading (Lm).

The Preparedness Index is calculated by the equation:

$$PI = \frac{Lm}{Lo} x\ 100$$

Where Lo = saccharimetric reading of the extract obtained with the extractor; Lm = mean of the extracts readings obtained with the PI determination apparatus.

APPENDIX B: Industrial conductivity meter and magnetic flow rate

The instrument is designed to measure the resistance of factory liquids a pair of electrodes. The temperature effect at the electrodes is negligible as the voltage at the electrodes is negligible as the voltage at the electrodes is about 50 mV (i.e. minimal effect from measuring current).

Measurements at factories are prone to 50 Hz noise induction. The instrument operates at 5000 Hz and the signal is processed by a frequency selective amplifier. This make it unnecessary to use shielded cables and ordinary ripcord can be used between the instrument and the electrodes.

Thirty meter ripcord has a capacity of 1600 pF. At 5000 Hz this is equivalent to an impedance of 20 kΩ (R= $1/2\pi f$ C) and has no influence on the measurements.

The conductivity meter has 4 ranges: 4 - 10 Ω

4 – 50 Ω

4 – 100 Ω

4 – 500 Ω

The linearity over each range is accurate to within 1 %. The output can be either 4 – 30 mA or 2 to 10 V, and the resolution is 4 ohms.

Equipment Calibration

- After switching on the positive and negative supply lines to each channel should be +15 V and -15 V.
- The output of generator should be measured at test point 1 and set to 20V p.p (oscilloscope) with RV1
  If no oscilloscope is available the voltage at TP1 should be measures with a suitable AC voltmeter and set at 7.15 V
- The range should be set at 100 Ω connected to the probe outputs.
  The output should measure at test point 2 (oscilloscope or AC voltmeter) and set to maximum with RV2. As RV2 and RV2 influence each other slightly the measurement at TP1 should be repeat once more.

- The switch S1 should be set at V and the output set to10 V with RV3. The probe output should be shorted and the output set to 2V with R4. These two measurements should be repeat a few times.

  To be able to carry out measurements outside the cabinet, a suitable extension cable is provided which should be plugged in Channel 1. Make sure both sides are plugged in the correct way.

APPENDIX C: Safmag electromagnetic flowmeter

The operation of an electromagnetic flowmeter is explained by reference to Faraday’s law of electromagnetic induction. This law states that the voltage induced across an electrical conductor, as it moves at right angles through an electromagnetic field, is directly proportional to the velocity of that conductor through the field. Mathematically this statement is represented as shown below:

$$E = \text{constant} \times B\ L\ V$$

Where E =the induced voltage; B =the electromagnetic field strength; L =the length of the conductor in the field; V =the velocity of the conductor (average velocity of the medium).

The volumetric flow of a conducting liquid or slurry is derived as follows: Let L = D (the diameter of the meter), Then E = constant x B D V

Volumetric flow Q = V A (where A is the Cross-sectional area of the pipe).

Combining the above equations it is seen that if field strength is held constant then E = KQ (where K is a constant), thus the induced voltage is directly proportional to the volumetric flow rate.

Performance Specifications

Performance specification System specifications are stated at reference conditions with frequency output.

Table 1. Flow meter characteristics

	Description
Accuracy	Display and frequency output ± 0.5% of rate for velocity > 0.5m/s ± 0.025% of full scale for velocity < 0.5m/s
Analog output	above error plus ± 0.008mA
Repeatability	± 0.1 % of rate
Temperature effect	± 0.01 % per deg. C
Mounting	Directly into pipeline at any attitude, ensuring that the flowtube remains completely full
Separation	Maximum recommended distance between the flowtube and the remote mounted signal converter is 100 metres
Sensor specification	The SAFMAG sensors are available in flanged and wafer format; Sizes (nominal bore) 25mm to 900mm (flanged format)

	40mm to 100mm (wafer format); Process connections Flat face steel flanges to mate with specified flange pattern (mild steel as standard) Metering tube 304 stainless steel
Pressure	Maximum pressure dictated by flange rating 25mm to 150mm 1000kPa as std sizes > 150mm 1600KPa as std for higher pressure consult factory
Electrodes	Non-removable 316 stainless steel, Hastelloy C, Monel (other - consult factory); Earth electrode Fitted as standard
Temperature Sensors:	Refer to limitations of lining material Sensors with integral transmitters: Ambient: -10 to + 50 deg. C Process fluid: -10 to + 70 deg. C, but refer to limitations of lining material
Environmental protection Sensors:	IP68 Sensors with integral transmitter: IP65
Sensor housing	Rolled 3CR12 cover welded to steel side panels
Electrical connections	(terminal box) Two 20mm IP68 glands
Conductivity	Process fluid must have a conductivity of at least 5 micro-siemens/cm
Display	Flow total and flow rate are continuously displayed on the 2 - line backlit LCD display. Illuminated display on remote version only
Power supply	115V or 230V ac ± 10%, 50 or 60Hz 12 - 30V dc
Power consumption	(Tube plus signal converter) 20VA maximum - DCMPU 200VA maximum - ACMPU
Ambient temperature limits	-10 to +50 deg. C
Output signals	4 - 20mA into 1000 ohm load (isolated output). 24V active pulse output to drive remote totaliser.
Analog output adjustment	Engineering units for flowrate are user selected. Output scaled to provide 4mA at zero flow, 20mA at the selected maximum flow value.
Pulse width	Adjustable from 10ms to 500ms
Software lockout	Changes in configuration data protected by user entered password
Output testing	Converter may be commanded to supply a specified output current
Low flow cutoff Adjustable	Below selected value outputs are driven to zero
Damping	Adjustable between 0.25 and 40 seconds

Range of measurements

The SAFMAG electromagnetic flow meter has a minimum full-scale velocity of 1 metre/second and a maximum full-scale velocity of 10 metres/second. Velocity is calculated from volumetric flow rate by using the following equation: V = 1273.24

Q/D2 Where: Q is the flow rate in litres/sec D is the nominal meter size in mm. So, The range of measurements was of configured from 0 to 310 l/s.

Conductivity

The minimum conductivity level for the SAFMAG is 5 µS/cm. Within wide limits the conductivity of the liquid has no effect on the calibration of a magmeter.

In an electrical series circuit, the voltage drops across the impedance's in the circuit must equal the applied voltage. In the equivalent circuit of a magmeter, the applied voltage is the flow signal picked up at the electrode, Zo is the output impedance of the flow tube, and Zi is the input impedance of the signal converter. % reduction in span = Zo / (Zo + Zi) x 100

The SAFMAG microprocessor signal converter utilises screen drivers to achieve high input impedance. The input signal from the electrode is buffered and applied to the electrode shields to provide protection against capacitance losses and process-generated noise. The input impedance is in excess of 1012 ohms.

The output impedance of the flow tube Zo is essentially the impedance of the process fluid, so it is necessary to convert conductivity to impedance, in order to calculate the percent span shift at differing conductivities.

For 1 microsiemen/cm (Zo = 106 ohms), % error = 0,0001%

For 1000 microsiemen/cm (Zo = 103 ohms), % error = 0,0000001%

It is clear from the above that even at conductivity's as low as 1µS/cm the span shift is insignificant if only the signal converter input impedance is taken into account. However, the signal cable will affect the Zi and must also be taken into account.

Signal converter specification:

The DCMPU signal converters are available for remote mount or integral mount. ACMPU signal converters are available only as remote mounted units. Both are capable of processing signals from fluid velocities between 0.01 and 10.0m/s for all flowtube sizes. Full scale is adjustable between 1 and 10m/s.

Interchangeability

Converters are fully interchangeable with all sizes of flowmeters and configurable on site. A DCMPU converter must be replaced with another DCMPU and likewise for an ACMPU. Flowtubes are flow-calibrated and assigned a calibration factor at the factory. This calibration factor is entered into the converter, enabling interchangeability.

Calibration

Factory Calibration and programming Before despatch the signal converter has been programmed, either to the factory standard or to those specifications advised by the customer. The SAFMAG electromagnetic flowmeter has been calibrated on the FLOWMETRIX calibration facility with direct trace ability to the National Standard. The unit will hold its stated accuracy indefinitely provided that it is correctly installed and undamaged. Instruction Manual 2013 SAFMAG Electromagnetic Flowmeter Page 15 FLOWMETRIX SA.

Calibration Coefficient: Due to the design characteristics of the various SAFMAG flowmeters, each has its own calibration coefficient (k-factor). This coefficient is determined during the factory calibration, and will not change unless the flowtube is damaged.

APPENDIX D: Correlation coefficient

The correlation coefficient of two random variables is a measure of their linear dependence. If each variable has N scalar observations, then the Pearson correlation coefficient is defined as.

$$\rho(A.B) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{A_i - \mu_A}{\sigma_B}\right)\left(\frac{B_i - B_A}{\sigma_B}\right)$$

Where μ_A and σ_A are the mean and standard deviation of A respectively and μ_B and σ_B are the mean and standard deviation of B. Alternatively. you can define the correlation coefficient in terms of the covariance of A and B:

$$\rho(A.B) = \frac{cov(A.B)}{\sigma_A \sigma_B}$$

The correlation coefficient matrix of two random variables is the matrix of correlation coefficients for each pairwise variable combination.

$$R = \begin{pmatrix} \rho(A.A) & \rho(A.B) \\ \rho(B.A) & \rho(B.B) \end{pmatrix}$$

A and B are always directly correlated to themselves. The diagonal entries are just 1, that is.

$$R = \begin{pmatrix} 1 & \rho(A.B) \\ \rho(B.A) & 1 \end{pmatrix}$$

APPENDIX E: Oscilloscope TDS 2014 Tektronix

The Tektronix TDS2014 Oscilloscope 100 MHz, 1 GS/s provides accurate real-time acquisition up to its full bandwidth, advanced triggers to isolate signals of interest, and 11 standard automatic measurements. The Tek TDS2014 Fast Fourier Transform (FFT) math function allows the user to analyse, characterize and troubleshoot circuits by viewing frequency and signal strength.

Features

- Channels: 4
- Sample Rate: 1GS/s
- Vertical Resolution: 8 Bits
- Equivalent Time Sample Rate: 1GSa/s
- Time BASE Range: 5ns/Div to 50 S/Div
- Memory Depth: 2.5 K
- Input Impedance: 1 MΩ with 20pF
- Vertical Sensitivity: 2 Mv/Div to 5V/Div
- Display Size: 5.6in.
- Bandwidth*1(1 Bandwidth is 20 MHz at 2 mV/div): 100 MHz
- Input Coupling: AC, DC, GND
- Time Base Range: 5 ns to 50 sec/div
- Time Base Accuracy: 50 ppm
- Horizontal Zoom:Horizontally expand or compress a live or stopped waveform
- Record Length: 2.5 K points
- DC Vertical Accuracy: ±3%
- Max Input Voltage: 300 VRMS CAT II; derated at 20 dB/decade above 100 kHz to 13 Vp-p AC at 3 MHz and above
- Position Range: 2 mV to 200 mV/div ±2 V; >200 mV to 5 V/div ±50 V
- BW Limit: 20 MHz
- Record Length: 2.5 K points

APPENDIX F: Functional Signal generator MFG 4202 characteristics

The instrument is an accurate testing instrument. It can output the function wave-form such as sine wave, square wave, rectangle wave, sawtooth wave and triangle wave. And the frequency and amplitude can be adjusted continuously.

Technical parameter

1. Output frequency Frequency range: 0.2Hz~2MHz ; seven ranges ① 0.2Hz-2Hz ② 2Hz-20Hz ③ 20Hz-200Hz ④ 200Hz-2kHz ⑤ 2kHz-20kHz ⑥ 20kHz-200kHz ⑦ 200kHz-2MHz 2).
2. Output signal impedance: 50Ω
3. Function output symmetry adjust scope: 20%~80% (±10%)
4. Output signal amplitude (peak-peak value): non-attenuate (2Vp-p~20Vp-p)±20% continuously adjustable attenuate 20dB (0.2Vp-p~2.0Vp-p)±20% continuously adjustable attenuate 40dB (20mVp-p~200mVp-p)±20% continuously adjustable The above are measured with load 1MΩ, the output signal amplitude will be half of standard at 50Ω load.
5. Output signal features: a) sine wave distortion:＜2%. b) triangle wave linear:＞99% (10%-90% of output amplitude). c) square wave rise edge times: less than 100nS (10%-90% of output amplitude). d) square wave fall edge times: less than 100nS (10%-90% of output amplitude). e) square wave rise and fall pulse less than or equal to 5%Vo (50Ωload). f) Test condition: frequency output: 10KHz, amplitude: 5Vp-p,warm-up for 20minutes.
6. Output signal frequency stability: less than ±0.1%/min (test condition is the same as the above)
7. Amplitude display (only for 50Ω load, at 1MΩ load, the real output amplitude is double of the displaying value): a) Display digits:2/3 digits (decimal point automatic select place). b) Display units: Vp-p or mVp-p. c) Display errors: Vo±10%±1d (Vo refers to the true value of output signal). d) Resolution: non-attenuate 0.2Vp-p 20dB attenuate:20mVp-p 40dB attenuate:2mVp-p
8. Frequency display: a) display range: 0.2Hz-2MHz. b) display effective digit: four or five digits.
9. Measurement errors: ≤0.5% 1
10. Time base: frequency: 12MHz frequency stability:±5x10-5
11. Working temperature: 0℃~40℃

12. Size: 270mm x 215mm x 100mm
13. Weight: approx.1.6kg.
14. Power applicability and consume: 110V/220V±10% 50Hz/60Hz±5%, power consume ≤ 15W

APPENDIX G: Description of the electrical equipment

The LM 339 is a circuit integrate consist of four independent voltage comparators that are designed to operate from a single power supply over a wide range of voltages. Operation from dual supplies also is possible, as long as the difference between the two supplies is 2 V to 36 V, and VCC is at least 1.5 V more positive than the input common-mode voltage.

Current drain is independent of the supply voltage. The outputs can be connected to other open-collector outputs to achieve wired and relationships.

The LM339 device is characterized for operation over the full military temperature range of –55°C to +125°C.

The Arduino is an open-source electronics platform based on easy-to-use hardware and software. Arduino boards are able to read inputs - light on a sensor, a finger on a button, or a Twitter message - and turn it into an output - activating a motor, turning on an LED, publishing something online. You can tell your board what to do by sending a set of instructions to the microcontroller on the board.

APPENDIX H: Matlab Program

To plot the estimated voltage (voltage estimated) as a function of time a program was written in Matlab, using the following steps.

1. To avoid errors in the simulation, the output voltage matrix is zeroed
2. It was determined that the resistive effect appears when the component of the voltage vector is five times larger than the previous component
3. Some of the components of the vector are empty (Not-a-Number, NaN). To correct this error, the component of the vector is filled with the value of the previous component
4. The value range for constants τ_1, τ_2, k_1, k_2 is adjusted
5. A matrix with all the constant vectors is created
6. The variation of voltage is computed using Equation 5.4 and considering the value given to the constant in the fifth step.
7. The mean error between the estimated voltage and the experimental voltage is calculated (MSE)
8. The method of single search in a closed range is used to determine the variation interval of each constant. For example, 80% of the variation interval of each constant is explored in the first iteration, which provides the maximum MSE between the estimated and experimental data with this new interval. The solution continues enclosing successively until the constants converge on a single value. If it does not happen, then return to step 4 and change value range for the constants τ_1, τ_2, k_1, k_2.

APPENDIX I: Constants of the voltage curves, and output/input voltage measured in the cane bed

Table 1. Constants of the voltage curves and output/input voltage measured in the cane bed

τ_1	τ_2	k_1	k_2	Z (m)	W (m)	V_{fin} (V)	V_{ini} (V)	Date
34.65	5.26	0.0073	0.0539	1.60	1.605	1.16	1.67	17/10/17
58.99	2.36	0.0063	0.1075	1.62	1.62	3.02	3.52	17/10/17
32.22	4.03	0.0061	0.182	1.62	1.62	2.63	3.22	17/10/17
17.44	3.14	0.0580	0.1011	1.64	1.64	2.90	3.20	17/10/17
10.08	9.71	0.0421	0.0476	1.64	1.64	1.48	1.84	17/10/17
41	0.31	0.0091	0.2656	1.64	1.64	1.10	1.53	17/10/17
54.28	2.39	0.0068	0.0859	1.65	1.65	0.99	1.56	17/10/17
36.16	4.31	0.0105	0.0268	1.65	1.65	1.14	1.60	17/10/17
17.44	0.14	0.0261	0.0004	1.65	1.65	1.06	1.46	17/10/17
47.83	2.39	0.0079	0.0577	1.65	1.65	1.05	1.53	17/10/17
0.112	4.59	5.63E-05	0.3340	1.65	1.65	3.60	3.81	17/10/17
40.88	1.02	0.0081	0.8783	1.65	1.65	3.26	3.96	17/10/17
22.75	0.71	0.0211	1.0340	1.65	1.65	3.39	3.94	17/10/17
54.54	0.33	0.0085	0.7186	1.66	1.66	3.05	3.60	17/10/17
19.25	1.66	0.0361	0.2777	1.67	1.67	3.40	3.65	17/10/17
55.12	0.31	0.0068	0.3145	1.67	1.67	1.05	1.50	17/10/17
41	1.29	0.0099	0.1456	1.68	1.69	0.97	1.51	17/10/17
47.83	4.30	0.0073	0.052	1.69	1.69	1.14	1.67	17/10/17
54.78	5.52	0.0077	0.026	1.70	1.70	1.13	1.70	17/10/17
23.76	0.21	0.0527	0.0054	1.28	1.40	2.62	3.04	21/09/17
17.44	0.10	0.0519	1.9523	1.31	1.33	3.88	4.43	21/09/17
33.58	1.37	0.0258	0.37	1.42	1.50	3.37	4.02	21/09/17
80.45	0.43	0.0057	1.5618	1.46	1.46	4.73	4.94	21/09/17
233.5	3.34	0.0021	0.1565	1.46	1.46	2.55	3.03	21/09/17
16.68	5.17	0.0017	2.9285	1.46	1.46	3.78	3.85	21/09/17
95.67	6.63	0.0045	0.1555	1.46	1.46	2.53	2.89	21/09/17

Source: Elaborated by the author