An Intelligent and Customized Electrical Conductivity Sensor to Evaluate the Response Time of a Direct Injection System

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***Abstract*—In pesticide application based on direct injection systems, the sprayer response time plays an important role for the spraying quality, mainly when operating in real time. The response time is defined as the time elapsed from the time of injection until the concentration of the mixture (water mixed with herbicide) reaches 95% of its regime value in the spray nozzles. Therefore, in the response time the transport delay and the rise time for achieving the desired concentration are considered. This paper describes an intelligent sensor mounted near the spray nozzles to measure the concentration response time in a herbicide direct injection system, which uses a highly stable sinusoidal excitation signal. The sensor calibration was performed with NaCl solutions at concentrations similar to those found in actual application conditions. Using an integrated system based on the Arduino platform, an algorithm was developed to relate the measurements to the response time. The integrated system comprises the sensor with its own sensing hardware, A/D converter, processing and storage capabilities, software drivers, self-assessment algorithms and communication protocols. The immediate application of the integrated system is in the monitoring of the response time of a precision pesticide application. The results point to the next generation of smart devices that have embedded intelligence to support decision making in precision agriculture.**

Keywords*–direct injection; response time; electrical conductivity; intelligent sensors

I. Introduction

Brazil has experienced in the last two decades a significant increase in the use of pesticides for agricultural production. Despite the significant growth of the area cultivated with transgenic seeds, a technology that promises to reduce chemical use in agricultural production, sales of these products increased by over 72% between 2006 and 2012 and is still rising up according to data from the Brazilian National Union of the Industry of Agricultural Defense Products [1], association which represents the pesticide manufacturers in the country.

In the same period, the area planted with grains, fiber, coffee and sugar cane grew by less than 19%, from 68.8 million to 81.7 million hectares, according to the Brazilian National Company for Supply [2]. This means that the average consumption of pesticides, which was just over 7 kilograms per hectare in 2005, rose to 10.1 kilograms in 2011, an increase of 43.2%. Although this amount indicates more protection for products and higher incomes, the uniform rate of application leads to soil and water contamination. A key approach to reduce environmental pollution is to use variable-rate application.

An approach to develop variable-rate sprayer technologies is to install automation and control procedures on conventional sprayers. In this direction the direct injection type of sprayer systems have been used along with electronic controllers. In order to adjust the sprayer operation, reference for variables such as working pressures, traveling speeds, and spraying concentration change rates can be selected to achieve the quality for spraying drop distribution.

The agricultural machinery and technologies available today enable variable-rate chemical application based on prescription maps or sensors [3]. Variable-rate application can be performed by varying the concentration of the chemical on-the-go using a direct injection system [4]. The direct injection system is an electronically controlled system in which the chemical is injected into the carrier stream. The direct injection system has separated chemical and carrier reservoirs and the chemical can be injected into the carrier stream in different positions.

In the literature, reports of systems to inject concentrated pesticides into diluent stream began to appear in the 70th decade [5]. In [6], Vidrine and collaborators tested the feasibility of injecting concentrated pesticides. In [7], Reichard and Ladd developed a field sprayer which included injection of pesticides at specific rates accounting for variations in travel speed. In [8], Chi and collaborators developed a flow rate control system which allowed the measurements of concentrated pesticides. In [9], Ghate and Perry developed a field sprayer based on the use of a compressed air to inject chemical into the carrier stream. In [10], Miller and Smith reported on development of a direct nozzle injection system. In general, during the spraying process errors can be observed. Research works on the evaluation of the application rate errors has been shown that errors are not only due to the deviations from the target flow rates but also due to interaction between the dynamics of the systems and sprayer response time. By now, is quite well known that the direct injection system sprayer response time depends on the sprayer dynamics and on the transport delay [11].

The transport delay is due to the flow rate and distance of the nozzle from the injection point. The farther the nozzle is from the injection point larger the mix uniformity and lower the cost but higher the transport delay of the sprayer. Several studies have appeared regarding to the performance of the direct injection sprayers and reducing their response time [12]–[20]. Therefore, the conventional implements can be reorganized to operate into variable-rate ones using control systems [21].

An advantage of the injection type variable rate application over pressure-based variable rate application is the ability to perform instantaneous changes in the concentration, as well as the herbicide type [22]. One of the most important injection-type systems is the direct injection, in which ingredients are pumped into a carrier fluid carrying them to the boom. The direct injection system advantage is in mixing the required amount of chemicals with water, saving the excess amount for later use [23]. A key indicator to determine the precision of a direct injection sprayer is the control system response time. The shorter its response time, the higher its field precision.

This paper presents an intelligent and customized electrical conductivity sensor (ICCS) for evaluation of the response time of direct injection sprayers. With the response time measurements in variable rate sprayers, a looking-ahead approach, which is useful to increase competitiveness and support sustainability in agriculture, can be performed.

After this introduction, this paper is organized as follows. Section II presents the theoretical background on the measurements of electrical conductivity, Section III presents the used materials and the methods for the development of the ICCS and the procedures for its validation. Finally, the results and discussions are presented in Section IV, followed by the conclusion in Section V.

II. Theoretical Background

The electrical conductivity, also called specific conductance, is the ability of a solution to conduct an electric current. The mechanism for the electrical current conduction in electrolyte solutions is not the same as for metals. In liquids, this process is performed based on the movement of solvated ions, which are attracted by an electrical field. Therefore, the physical-chemical process is related to the occurrence of combination between the molecules of a solvent with molecules or ions of the dissolved substance. However, electrolyte solutions obey Ohm's law in the same way as the metallic conductors. When powered by direct current passing through the body of the solution, the conductance denoted G is defined as the inverse of the resistance expressed in Ω^{-1} or Siemens (S). However, the conductance G of a homogeneous body having uniform section is proportional to the sectional area A and inversely proportional to the length ℓ, then:

$$G = \frac{\sigma A}{\ell} \tag{1}$$

where the proportionality constant σ is the conductivity and given in S/m. The ratio ℓ/A is called the conductivity cell constant and depends on the instrumentation used. The conductivity increases with increasing temperature. Furthermore, the conductivity of a solution depends on the number of ions present and for this reason the most common is the use of the molar conductivity defined as:

$$\Lambda_m = \frac{\sigma}{M} \tag{2}$$

where Λ_m is the equivalent conductivity or the molar conductivity in Sm^2/mol and M is the molarity or molar concentration in mol/L. The molar conductivity varies with the concentration of the electrolytes. A major reason for this effect is the change in the number or mobility of the ions present. The first case occurs in weak electrolytes, where the dissociation of ions in a solution is not complete. The second case occurs on strong electrolytes, where in the solution the dissociation of the molecule into ions is total, resulting in a very strong interaction between the oppositely charged ions, and can reduce your mobility.

The study of electrical conduction in ionic solutions would be useful for a quick and routine analysis of solutions, since it is a simple measure related to the properties of the solution. In this context, the conductivity of a solution in a cell having an arbitrary dimension can be obtained by determining the cell constant by measuring the resistance of a solution of known concentration. After the cell constant is determined, the values of conductivities of different solutions can be obtained from experimental measurements data. For devices that do not have the automatic temperature compensation system, the conductivity must be determined at 25°C which is the reference temperature.

In solutions, yet it is necessary to correct the conductivity observed by subtracting the conductivity of the solvent, i.e., to get the value of $\sigma_{corrected}$. Therefore, the molar conductivity Λ_m shall be written as:

$$\Lambda_m = \frac{\sigma_{corrected}}{M}. \tag{3}$$

Thus, turning the unit concentration mol/L to mol/cm^3, the equivalent conductivity Λ_m between two electrodes spaced 1 cm away due to 1 mol of substance may be given as:

$$\Lambda_m = \frac{1000\sigma_{corrected}}{M}. \tag{4}$$

Then, for a parallel plate sensor, the conductance G can be determined based on the molar conductivity Λ_m, the corrected specific conductivity of the electrolyte $\sigma_{corrected}$, the total ionic concentration M (mol/cm^3) of the substance in the electrolyte solution, and the conductivity cell constant ℓ/A in the form:

$$G(A, \ell, \Lambda_m, M) = \left(\frac{\Lambda_m M}{1000}\right)\left(\frac{\ell}{A}\right). \tag{5}$$

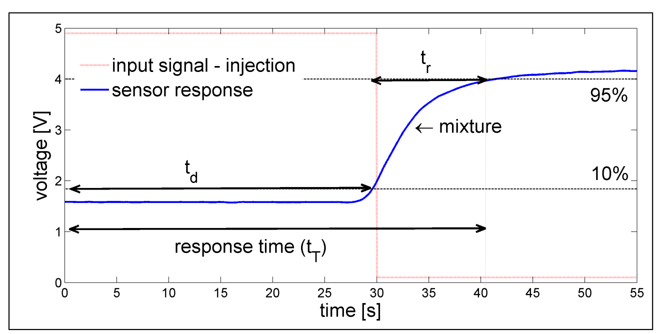

Figure 1. The delay time t_d, rise time t_r and response time t_T involved in a typical injection system as defined in [24]. The red line indicates the behavior in time of the concentrated mixture (water-NaCl) as an injection input.

Peck and Roth defined response time (t_T) as the period from the instant the injection begins until the chemical concentration rate reaches 95% of the equilibrium rate [24]. The rise time t_r and transport delay t_d characteristics of a sprayer proposed by these authors are shown in Figure 1. A 95% concentration rate corresponds to the chemical concentration of the spraying, which is necessary for satisfactory weed control [25].

III. Material and Methods

The components of the customized smart sensor designed to measure the response time in spraying systems using direct injection of pesticides are shown in Figure 2. For the construction of the smart sensor, voltage regulators, an integrated circuit for a function generator having the capability of frequencies adjustment, opto-isolators and filters were used. Operational amplifiers were used in the active analog filters, non-inverting amplifier drives and isolators circuits. A power transistor was used to drive the injection pump and optocouplers were used to isolate the power circuit from the control circuitry.

A. Excitation Circuit

An excitation circuit for the conductivity sensor was constructed to provide a sinusoidal signal with stability, appropriate frequency and magnitude (Figure 3). The circuitry comprises a sine wave oscillator, a high-pass filter, two insulators and an inverting amplifier circuit (Figure 3). The circuitry was developed to produce signals with high stability and accuracy in an operating frequency range of 0.01 Hz to 1 MHz (Figure 4).

For the generation of the sinusoidal signal an XR2206 integrated circuit which produces sinusoidal signals with considerably low harmonic distortion was used [26]. The oscillator frequency was set to 1.0684 kHz, which is suitable for the application and useful to reduce the electrolysis and the polarization of the solution. In order to tailor the signal for the sensor application considered, a high-pass filtering and a signal amplification module were also used. After conditioning, the signal was appropriate for use presenting voltage values limits as V_{max} = 4.96 V and V_{min} = -4.92 V.

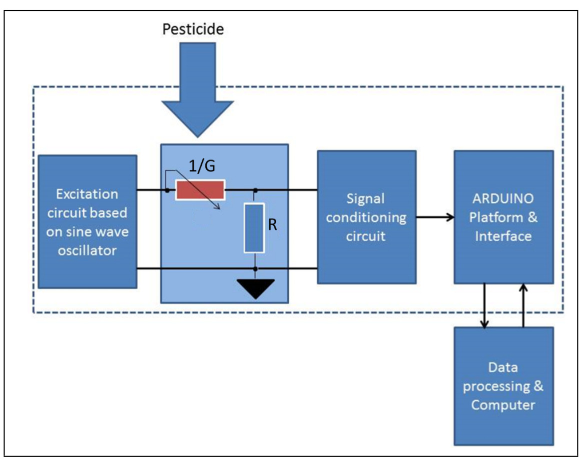

Figure 2. Block diagram of the customized intelligent sensor for response time measurements in spraying systems based on direct injection of pesticides.

B. Signal Conditioning

For signal conditioning, the operational amplifier LF347 integrated circuit, which presents broad bandwidth range (4 MHz), high Slew-Rate (13 V/s), high impedance input ($10^{12}\,\Omega$) and fast settling time (2 μs), was used [27]. The use of the OPA344 operational amplifier (low voltage) with an output type Rail to Rail [28] was considered to isolate and protect the Arduino Uno platform against voltage surges or malfunctioning of the mounted circuits.

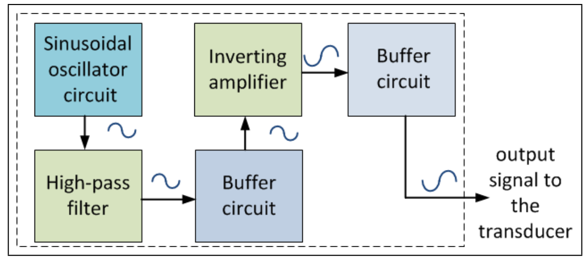

Figure 3. Block diagram of the excitation circuitry.

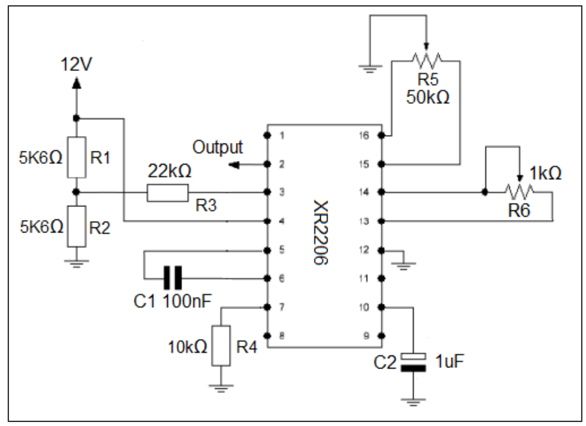

Figure 4. Circuit for the excitation signal generator.

The output of the isolator circuit is limited to voltages from 0 V to 5 V, safe input voltage range for the analog/digital converter (ADC) of the Arduino Uno platform. This ADC has 6 channel 10-bit resolution with absolute accuracy of $\pm$2 LSB ($\approx$15mV), and maximum sample rate of 15 kS/s. The Arduino Uno is an electronic prototyping platform, hardware open and single board, designed with an Atmel AVR microcontroller with built-in input-output support and a standard programming language with origin in Wiring projects, essentially based on C/C ++ [29]. The Arduino Uno platform was used for data acquisition, signal conditioning, computational processing, intelligence aggregation [30], and also for activating the sprinkler system of the injection pump through the LabVIEW® software. The use of a buffer circuit, commonly called unity gain buffer, ensures isolation between the two separate stages of the circuit, and the electrical characteristics of a stage does not influence the characteristics of the other. The frequency response and impedance characteristics of the isolation circuit were analyzed through computer simulations, performed in LTspice® software. The output signals of each of the stages of excitation circuitry were obtained using an oscilloscope Tektronix TDS2012B and graphics were later built in the Matlab® software.

C. Sensor Mounting

Based on the theoretical backgrounds previously presented, a set of parallel plates conductivity type transducers have been built and analyzed for measuring the response time based on the electrical conductivity of the herbicides present in an agricultural direct injection spraying system. Two stainless steel electrodes with a diameter of 5 mm were used. These transducers were constructed by using a polyacetal base and assembled direct into the nozzle bodies equipped with a diaphragm check valves. For the analysis of the sensor with a static fluid, the electrodes were coupled to the base and spaced at three different distances chosen as 0.5 mm spacing, 1.5 mm and 1 mm, resulting in a set of constant of cells equal to 0,255 cm^{-1}, 0,500 cm^{-1} and 0,764 cm^{-1}, respectively. The Figure 5 illustrates the positioning and location of the sensor for response time measurements.

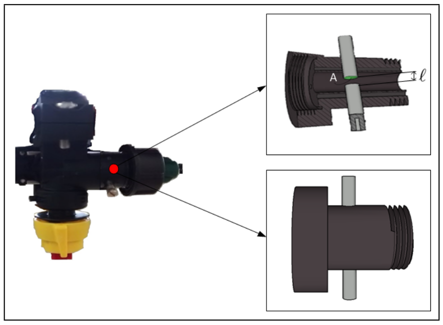

Figure 5. Details of the smart sensor customized to measure the response time of a system of direct injection of pesticides.

D. Sensor Calibration

In order to validate the developed sensor, a real experiment to measure the response time of a sprayer system based on direct injection was performed. The experiment was set for a cell constant of 0.500 cm^{-1}. Furthermore, the sensor was directly assembled into a spray nozzle holder arranged as shown in Figure 6.

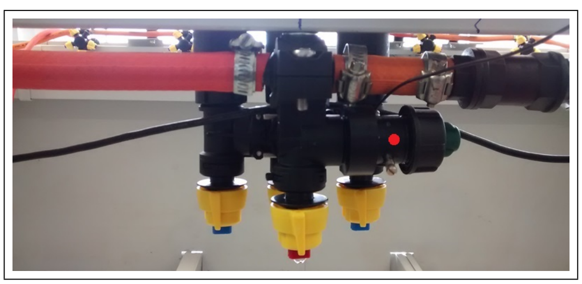

Figure 6. Instrumental arrangement for validation of the intelligent sensor to measure response time of a direct injection sprayer with TeeJet® QJS Multiple Nozzle Bodies e-ChemSaver.

For analysis in real time, the conductivity was measured and the results were processed via LabVIEW® software. Additionally, an Arduino Uno platform was used to capture the analog signals from the sensor, which were previously conditioned for digital measurements, and further processed by computational methods.

The calibration was performed using a commercial conductivity meter from the Tecnopon mCA150 with an operating range of 0 to 200 $\mu S/cm$, resolution of 0.1 $\mu S/cm$ (for solutions in the range of 0 to 200 $\mu S/cm$), 2% of full scale accuracy and 1% of full scale precision [31]. The measurements performed with the commercial conductivity meter were checked with a standard KCl solution (0.02000 mol/L). Static tests were carried out for the analysis of solutions consisting of water and NaCl. The procedures were performed for three different cell constants.

IV. Results and Discussion

The computational processing of data and analysis with the developed conductivity sensor was performed using the LabVIEW® software, after the analog/digital conversion and signal conditioning with the Arduino Uno platform. The use of the electronic Arduino Uno platform and the LabVIEW® interface allowed the aggregation of intelligence for self-diagnostic of the ICCS, as well as its self-assessment based on the use of a specific pseudo-code algorithm (Figure 7). The data valid flag was determined experimentally, i.e. based on the dynamic range of the ICCS, defined by 0.50V±2LSB $< V_{ICCS} \leq$ 4.90V±2LSB, which is related with the accuracy allowed by the internal ADC of the Arduino Uno platform.

```
Initialization (TIMER, SERIAL, ADC);
if 0.50V < V_ICCS ≤ 4.90V then
  | data valid flag = true;
else
  | data valid flag = false;
end
while true do
  | if data valid flag == true then
  |   | read temperature ADC;
  |   | read conductivity ADC;
  |   | calculate CONDUCTIVITY;
  |   | send CONDUCTIVITY to SERIAL;
  | else
  |   | send ERROR to SERIAL;
  | end
end
```

Figure 7. Pseudo-code of the algorithm for self-assessment and self-diagnostic.

The calibration results identified the relation for a better accuracy for the conductivity sensor, which is dependent on the conductivity cell constant of the transducer. The shorter the distance between the faces of the electrodes for a same section greater will be the accuracy of the measurements. The calibration curves are shown in Figures 8, 9 and 10 for constant cells given by 0.255 cm^{-1}, 0.500 cm^{-1} and 0.764 cm^{-1}. The individual time responses and the transport delay time for each repetition (Figure 11) were analyzed based on the use of the conductivity sensor and its application in an actual spraying system with a water-NaCl solution flow of 16 L/min and pressure equal to 200 kPa. Table I shows the experimental values obtained for determining the response time and the delay times.

TABLE I. Experimental values of delay and response times.

Flow (L/min)	*Repetitions*	V_{min} (0%)	V_{max} (100%)	t_d (s)	t_T (s)
16	1^{st}	1.583	4.160	29.560	42.480
	2^{st}	1.574	4.170	28.800	41.550
	3^{st}	1.568	4.150	28.360	41.400
23	1^{st}	1.558	3.989	22.530	32.810
	2^{st}	1.534	3.964	22.520	33.010
	3^{st}	1.548	3.969	23.090	33.770

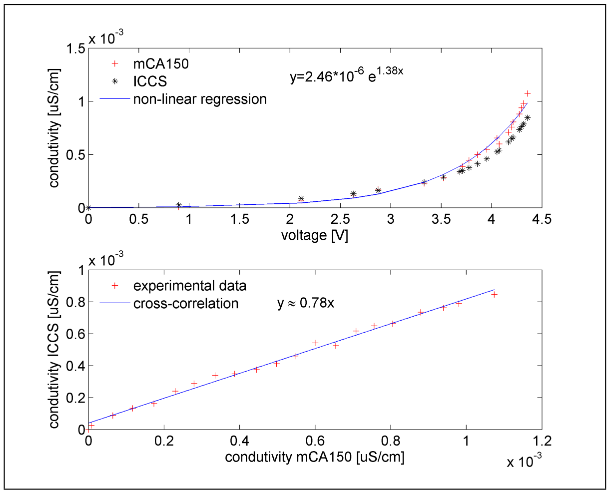

Figure 8. Calibration curves and comparison of measurements of the electrical conductivity from experimental solutions obtained with the intelligent and customized sensor with cell constant of 0.255 cm^{-1}.

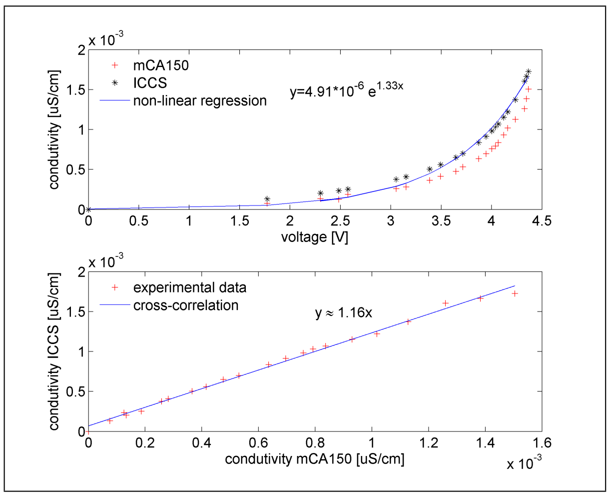

Figure 9. Calibration curves and comparison of measurements of the electrical conductivity from experimental solutions obtained with the intelligent and customized sensor with cell constant of 0.500 cm^{-1}.

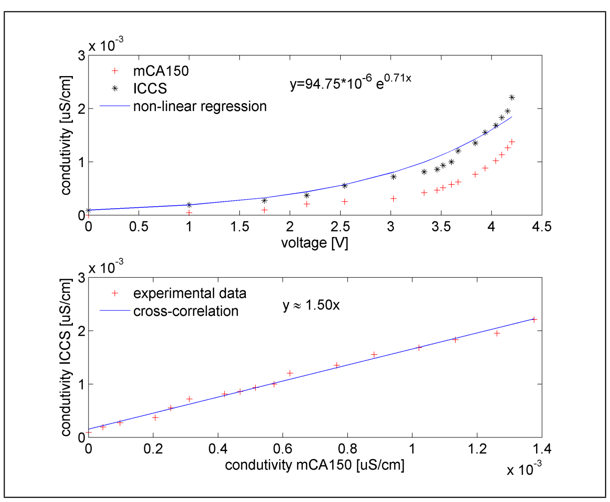

Figure 10. Calibration curves and comparison of measurements of the electrical conductivity from experimental solutions obtained with the intelligent and customized sensor with cell constant of 0.764 cm^{-1}.

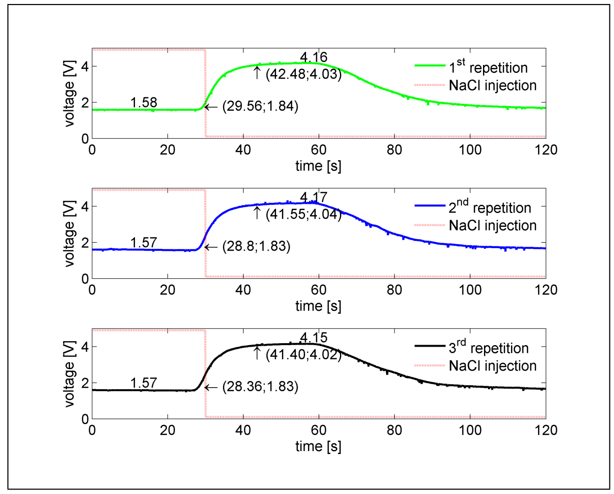

Figure 11. Transients and transport delay times of the sprayer with the conductivity sensor assembled in an actual spraying system with water-NaCl solution flow of 16 l/min and pressure equal to 200 kPa.

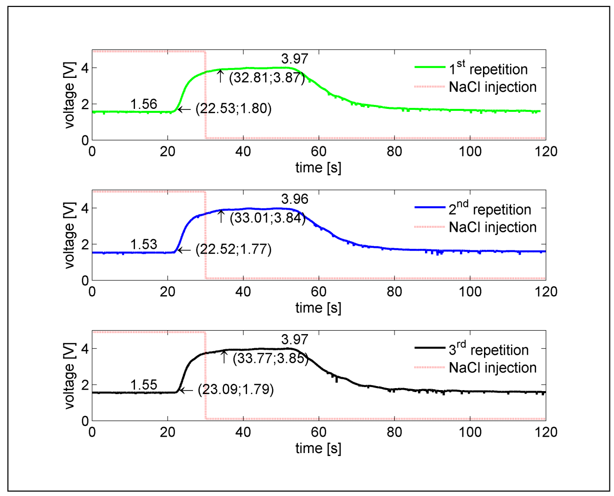

Figure 12. Transients and the transport delay times obtained with the intelligent conductivity sensor assembled in an actual spraying system with water-NaCl solution flow of 23 l/min and pressure equal to 400 kPa.

The obtained results of the dynamic responses for the three repetitions demonstrated the sensor accuracy and reliability. For this experimental arrangement, the average delay time was 28.91 s and the average response time 41.81 s.

A second set of experiments was conducted and the results are shown in Figure 12. In this case, a water-NaCl solution flow of 23 l/min and pressure of 400 kPa were used.

Also, is important to observe that reliability effects and faster circuits have higher current densities, lower voltage tolerances and higher electric fields, which make integrated circuits more vulnerable to electrically failure. The integrated circuits used for the intelligent sensor represent new generations of electronic devices and they provided good performance. Furthermore, the use of the polyacetal base for the intelligent sensor requires a failure analysis.

These procedures for reliability assessment are crucial for the end user as adjustments to electrical conditions and thermal management, since the electrical conductivity is dependent of the temperature of the flows related to the mixture of water plus pesticide.

The results obtained for the sprayer system having a flow rate equal to 23 L/min and pressure of 400 kPa, as occurred previously, have shown again, accuracy and reliability in achieving results based on the developed sensor. The average delay time was of 22.71 s and the average response time 33.20 s.

V. Conclusion

An intelligent sensor to measure the response time of spray systems based on direct injection was presented. The results have shown its usability in real time applications. The decision to embed the smart sensor directly in the sprayer nozzle provides a scenario, where the input data from the physical sensor could be analyzed by various knowledge-based routines. The sensor output could be raw data or preprocessed information. This information could be in the form of a flag, which shows a confidence level of the response time for pesticide applications.

The results based on the calibration curves for the sensor in three different assemblies showed that the accuracy of measurements depends directly on the conductivity cell constant. However, to determine the response time of a direct injection system of pesticides, one can use a customized sensor with greater spacing between its electrodes to get an adequate sensitivity for sensing the degree of the mixture involving pesticide plus water. Thus, the time involved in the path traversed by the mixture in the sensor can be minimized.

The results of the sprayer system response time with direct injection obtained in this research work have shown that the smart sensor developed has good repeatability, reliability and practicality. Therefore, the results also show the decreasing of the response time with the increasing of the flows, resulting from the increased speed, in which the mixture of water plus the pesticide goes through the system.

The use of intelligent sensor is anticipated to provide additional information than that of traditional sensors. The information provided by an intelligent sensor can include actual data, corrected data, validity of the data, and reliability of the sensor.

Furthermore, such ICCS development attend future perspectives for practical applications, potential benefits for sustainability, as well as precision agriculture processes.

Acknowledgment

The authors acknowledge the financing support from the Brazilian Agricultural Research Corporation (Embrapa Instrumentation, Process MP2 No. 02.11.07.0.25.00.00) as well as from the CNPq Brazilian agency under grant 306477/2013-0.

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