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Analysis of Different Probe Geometries for Ethanol Fuel Qualification Using Time-Domain Reflectometry

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Abstract—This paper proposes sensors based on the time-domain reflectometry (TDR) technique for qualifying ethanol fuel. Four different probe geometries were proposed: bifilar, microstrip, coaxial, and helical. All probes allowed qualification of ethanol adulterated with water. Helical probe showed the best response. Thus, this proposal contributes to the development of electronic tongues.

1. INTRODUCTION

Ethanol has become an important fuel for the automotive industry in several countries. Alcohol has been considered an alternative to fossil nonrenewable fuels, with a world production of almost 90 billion litters in 2011 [1]. However, the illegal adulteration of automotive fuel can cause two kinds of problems: firstly, there is the pollution resulting from irregular fuel burning. Whereas fuel burning naturally produces toxic gases, the use of adulterated products results in more dangerous pollution, with consequences for the environment and even for human health. Secondly, adulterated fuel leads to reduced engine lifetime. Effects such as detonation may damage the engine pieces and affect its performance. In addition, fuel adulteration impacts countries economy due to tax evasion and unfair competition.

Besides, usual fuel analysis methodologies require relatively complex laboratory equipment, including the use of flash point tester, conductivimeter, and gas chromatograph [2]. Hence, the TDR technique is proposed here as an auxiliary to the analysis, since it is a simple, fast, compact, and non-destructive method for ethanol qualification. Previous studies already showed promising results regarding this technique for characterizing ethanol adulterated with water [3]. We further expand the studies by proposing geometry variations in the probes, aiming at higher sensitivity and performance of the sensors for ethanol fuel analysis.

2. TDR TECHNIQUE

The TDR technique consists in applying electromagnetic wave pulses over a transmission line and measuring its time-dependent response or echo [4, 5]. This method is based on transmission-line principles in which a reflection of the incident wave occurs if there is an impedance mismatch between the load and the line characteristic impedance. The main factor that allows analyzing fuel or other medium by TDR is the speed of the electromagnetic signal propagation [5]. Considering a TDR probe as a lossy transmission line, the reflection time Δt that an electromagnetic wave takes to travel forth and back to the beginning of the line is [7]:

$$\Delta t = \frac{2L\sqrt{\varepsilon_{eff}}}{c} \tag{1}$$

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where L is the probe length, ε_{eff} the effective electrical permittivity of the sample, and c the speed of light in vacuum. Equation (1) expresses the direct relationship between time variation Δt and ε_{eff}, which represents a constitutive parameter of the medium [6–8]. Also, the equation presents a linear behavior between Δt and probe length L.

3. METHODOLOGY

The methodology consisted in simulating some probe geometries using the Agilent EMpro software, the fabrication of the probes, and the characterization with different ethanol-water proportions. We designed four different probe geometries: bifilar, coaxial, microstrip, and helical lines, as shown in Fig. 1. The first three kinds of lines are commonly used for soil moisture TDR sensors [9], while the fourth one, the helical (proposed here), consists of two wires twisted in parallel in order to obtain a greater effective length. The helical probe was made of copper wires with diameter of 1.5 mm. The wires were manually coiled around a metallic tube with diameter of 9 mm (the same size of the loop diameter LD).

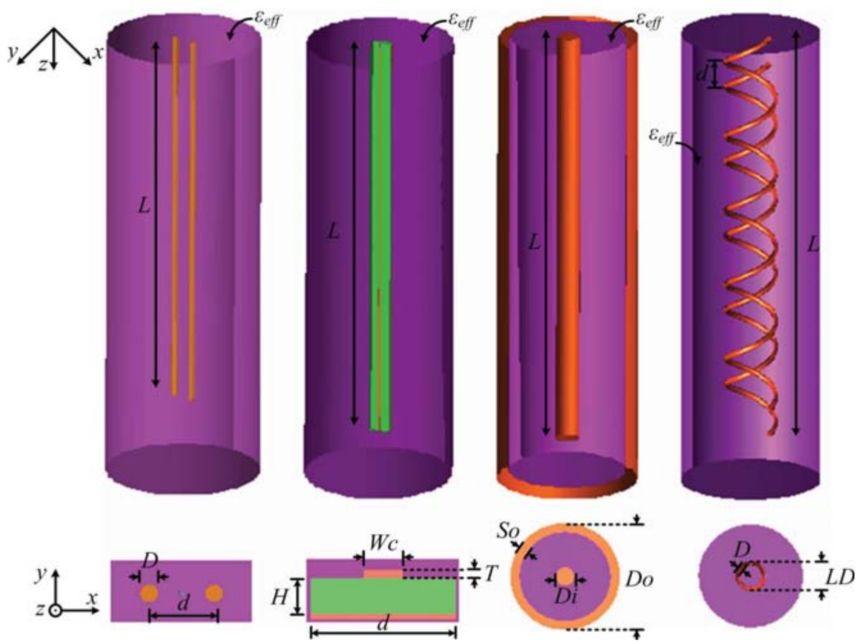

Figure 1. Simulated probe geometries: bifilar, microstrip line on FR4 substrate, coaxial, and helical, sequentially.

Table 1. Probe geometrical parameters.

Bifilar Sensor		**Coaxial Sensor**	
Rod diameter D	1.5 mm	Inner conductor diameter Di	1.5 mm
Distance between rods d	1 mm	Outer conductor diameter Do	18 mm
Length L	10 cm	Length L	10 cm
Microstrip Sensor		**Helical Sensor**	
Conductor width Wc	0.6 mm	Rod diameter D	1.5 mm
Substrate width Ws	6 mm	Distance between rods d	2 mm
Conductor thickness T	0.1 mm	Number of loops N	5
Substrate thickness H	1.5 mm	Loops diameter LD	9 mm
Length L	10 cm	Length L	10 cm

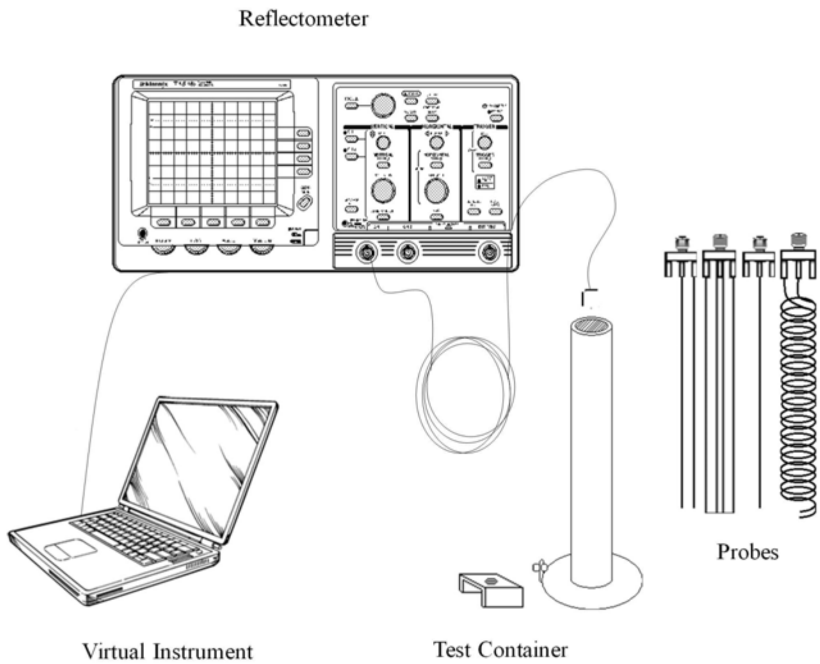

Figure 2. Experimental setup for ethanol fuel analysis.

The distance between the loops was controlled with help of a paquimeter. As a requirement, all the probes were designed with the same length, fitting the test container. The parameters for each probe are shown in Table 1.

The experimental setup is illustrated in Fig. 2. It employs a reflectometer Tektronix 11801B with a TDR sampling head controlled by a Virtual Instrument developed with LabVIEW from National Instruments. The reflectometer generates a step signal with a rise time of 7 ps and an uncertainty of 0.005 ps. A stainless steel tube with 20 mm diameter and 200 mm length was used as the samples container. The probes were soldered to SMA connectors, which were connected to the reflectometers sampling head by a 50 Ω coaxial cable.

A digital weighing scale was used for preparing the sample. The samples were then prepared in the proportions: 99.5%, 95.4%, 93.95%, 92.5%, 85.7%, 79.45%, 73.54%, 67.88%, 42.51%, and 0% m/m (ethanol/total mass).

4. RESULTS AND DISCUSSION

The TDR response for each topology is illustrated in Fig. 3. The overshoot indicated as probe start corresponds to a mismatch between the SMA connector and the probe itself (the soldering point) and permits to visualize the beginning of the electromagnetic signal traveling. The reflection time is given as the time between the "probe start" and the intersection point of the estimated regression lines fitting the base and the rise sections of each curve.

The microstrip line showed the lower reflection time (less than 2 ns from the start of the probe). This behavior can be explained by the influence of the substrate: FR-4 is a glass fiber with ε_r about 4.6 (less than both water and ethanol). Part of the energy injected in the probe travels along the substrate, while another part goes through the sample around, such that the average travel time decreases due to an effective permittivity.

Both coaxial and bifilar lines were responsible for a reflection time close to 3 ns, which is higher than the microstrip for the same probe length ($L = 10$ cm). The helical topology presented the highest reflection time among the probes, around 5.5 ns; whereas all of the lines were made with the same

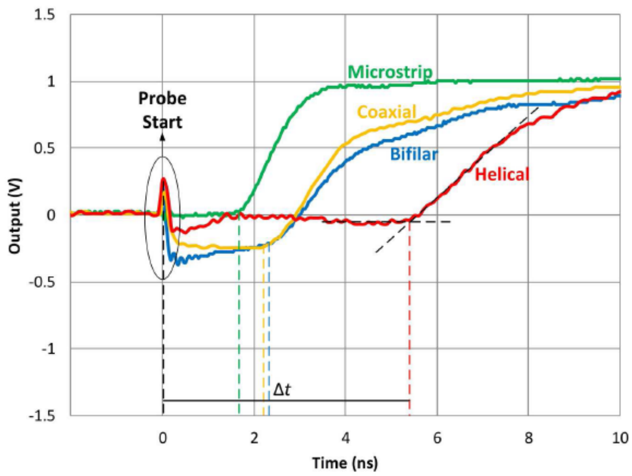

Figure 3. TDR response for 99.5% ethanol. Comparison among the probes. The reflection time Δt of the helical probe is indicated to illustrate its determination.

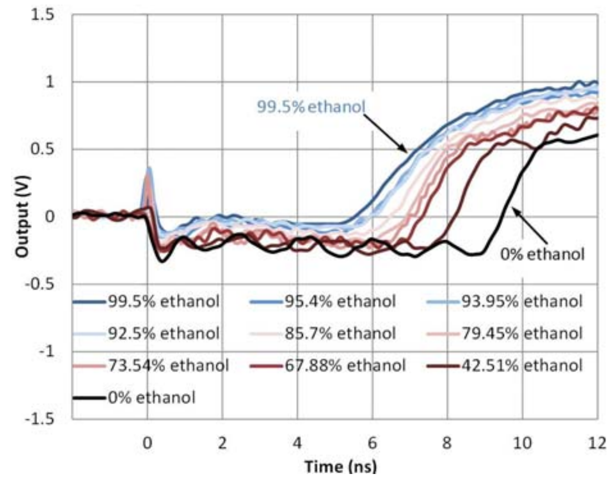

Figure 4. TDR response of helical probe for different water contents in ethanol. The reflection time increases directly with the decreasing of ethanol fraction.

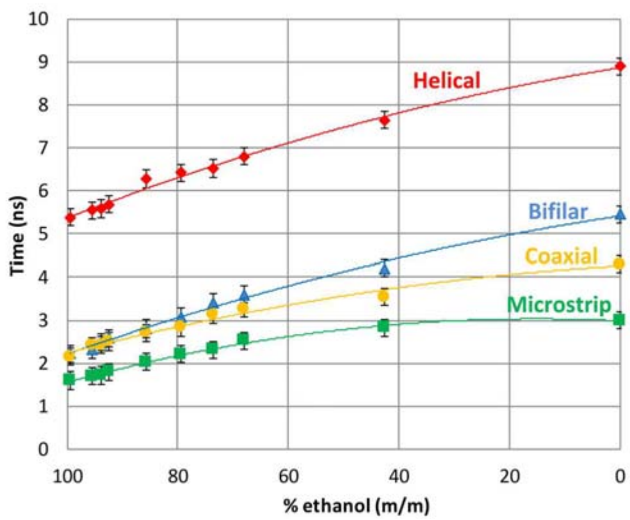

Figure 5. Reflection time for different TDR probes and ethanol-water concentrations.

physical length, the twisted wires for the helical probe were designed in order to achieve a greater effective length.

Figure 4 shows the TDR response for the helical probe. It is possible to visualize the relation between electrical permittivity and reflection time. One can verify that ethanol samples are responsible for faster echoes since its electrical permittivity is lower than water. The curves closer to the 99.5% of ethanol indicate acceptable contents of water in ethanol, according to the Brazilian regulation, while the curves with proportion greater than 92.5% of ethanol represent adulterated samples. Similar curves were acquired for the four different probe geometries. Then, the reflection times were obtained for each probe and each ethanol concentration.

Figure 5 presents the curves of the reflection time vs. ethanol concentration for all probes. Uncertainty was calculated as ± 0.2 ns for the reflection time and $\pm 2 \times 10^{-5}\%$ for ethanol mixtures. The experimental results show that the helical probe has much greater reflection time, which indicates higher dynamic range and precision than any of the other probes. In contrast, the microstrip probe shows lower reflection times as consequence of the substrate. Bifilar and coaxial lines presented intermediary response, with similar reflection times for 99.5% ethanol. Fig. 5 also presents well-defined trend lines for all probes in the whole concentration range, showing slightly higher sensitivity for higher concentrations of ethanol. The curve for helical probe presents sensitivity about 0.05 ns/1% in this range, in such way that the proposed methodology is promising. Naturally, improvements must be made to minimize the uncertainties in the range of interest for ethanol fuel qualification (from 92.5% to 95.4%).

5. CONCLUSIONS

The TDR technique is proposed as a methodology for fuel qualification. The technique is investigated by studying variations in the probe geometries. Four different geometries were designed and simulated, including typical geometries and the so-called helical geometry originally proposed here. Prototypes of these probes were fabricated and tested for ethanol with different contents of water. The experimental results showed that the helical topology presented a range of response about 2 to 3 times bigger than the others, without any considerable distortion in the TDR signal for this unusual 3D TDR probe. This characteristic may enable the use of the probe with detection circuits working at lower frequencies.

Another factor worth mentioning is that the probes studied may be applicable not only to fuel qualification, but also to the analysis of different mediums involving variations in their electrical permittivity, making it a contribution to the development of electronic tongues.

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