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A simple impedance method for determining ethanol and regular gasoline mixtures mass contents

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Abstract

A simple electric impedance sensor embedded in ethanol and regular gasoline blends for determining mass ratios was built and tested in the present work. It was carried out a quantitative evaluation of mixtures for several fuel mass ratios in the temperature range of −10 to 40 °C. A non-linear dimensionless electrical conductivity–fuel mass ratio correlation was obtained for a 0–100% ethanol mass content in gasoline. Tests at different temperatures showed that the temperature had an important influence over the mixture bulk conductivity and sensor signal. This work was carried out following the Brazilian automotive industry trend of using ethanol–gasoline mixtures at any proportion to power passenger automobile engines.

Keywords: Ethanol; Gasoline; Conductivity; Impedance sensor

1. Introduction

The use of ethanol–gasoline blends as a fuel is an important alternative strategy for gradually replacing hydrocarbon fuels for a renewable energy source in view of a future expected petroleum depletion. As a consequence, many researches have carried out studies on the effect of such fuel blends on the performance as well as on pollutant emission issues of engines. Palmer [1] examined various blend rates of ethanol–gasoline fuels in an engine, which indicated an increase in engine performance of about 5% in shaft power, 5% of the octane number, and a reduction of 30% in concentration of CO for 10% ethanol addition in gasoline. In Ref. [2], the authors tested from 10 to 40% ethanol content in blended fuels in a variable-compression-ratio engine, which resulted in an octane number improvement at the expense of a heating value reduction. Different blend rates of ethanol–gasoline fuel in engines was studied in the work of Ref. [3], and the authors found that the ethanol could reduce CO and UHC emissions to some degree, which was found to be apparently caused by the wide flammability and oxygenated characteristic of ethanol. From the literature review, it is understood that ethanol–gasoline blended fuels can effectively lower the pollutant emission without major modifications on the engine design [4]. Moreover, ethanol (C_2H_5OH) can be used as automobile fuel alone or in mixtures containing about 20% ethanol by volume, and can be safely used without causing any damage to the construction of the engine, as it has been used in Brazil for several years. A phase separation is observed in ethanol–gasoline mixtures when the amount of water present in the mixture is over a certain limit. In addition to the environmental and technical considerations, the use of gasoline and ethanol mixtures at different proportions for powering internal combustion engines has become very popular because it gives the consumer the power of making decisions on which fuel one will refuel the automobile tank based on pump price and availability without any further technical restriction. The design and the development of Alternative Fuel Vehicles (AFV) technology has presently

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been one of the main focuses of the automobile industry in anticipation of the future fossil fuel limitation, which has opened new opportunities for other fuels usage in combination with conventional gasoline. Among the several techniques, the Flexible-Fuel Vehicles (FFV) has had a special attention because of practical and economical viability aspects for mass commercialisation as it has already occurred in some countries. Consequently, it is desirable to discuss the features of FFV's and look at the possibility of including the necessary adjustments on engines, such as equipment and control systems, and a fuel blend sensor (an impedance type or an optical type, for instance) to detect the percentage of ethanol and gasoline mixture in course. For instance, there exists a measurable variation in bulk conductivity of ethanol and gasoline mixtures with some water content that may furnish a characteristic electrical signal to indicate fuel composition [5]. Bulk electrical conductivity may be measured by using an impedance sensor, which can be very efficient for automobile applications as well as for other multi-fuel combustion systems. The sensor can be mounted on the fuel feeding line prior its injection to provide an electrical signal to an on-board computer, which can optimise ignition timing and air/fuel ratios in real time as demanded. There are many different impedance sensor construction techniques proposed in the literature. As an example, Ref. [6] discusses and presents some details such as transducer geometry, sensitivity, and calibration.

The main objective of this work was to correlate the mass ratio of ethanol and regular gasoline blends to their bulk conductivity, obtaining a transference function for control purposes. All test results were reduced in order to obtain the transference function, which is basically the calibration curve of the sensor over a large range of working temperature and mass ratios.

2. Impedance technique

If an alternate voltage (AC) is applied to any medium, the ratio voltage to current (V/I) is known as the impedance. In many materials, especially those that are not generally regarded as electrical conductors, the impedance varies with the frequency of the applied voltage source. Such behaviour is due to the physical structure of the material, to chemical processes within it, or to a combination of both. In addition, if the overall impedance is obtained over a selected frequency range, it is possible to correlate the overall impedance to the electrical bulk properties, namely, the conductivity and capacitance.

Since impedance measurement is a repeatable and non-destructive technique, it can provide valuable insights into the behaviour of a huge variety of substances, components, and systems, by using an electrical analogy approach. For example, measuring the overall impedance of a fuel mixture can yield to a precise information about the mass content in a binary fuel blend.

2.1. The electrical impedance sensor

An ideal fuel sensor must be capable of operating not only at any fuel blend ratio but also as at any other operational condition found in automobile engines as well. Electric impedance sensor types have already existed in operation for many decades and they are largely known in scientific and industrial environment, mainly in systems where liquid–vapour or liquid–gas are present.

The geometry of the transducer used in this work was established having in mind some constraints, such as: simplicity, reliability, and low manufacturing cost against good sensibility, accuracy, and low response time. These are some of the usual requirements of the automotive industry. These conditions impose important restrictions for an impedance sensor usage from the automotive industry point-of-view in FFV's, since a reliable injection system control should work at any mixing ratio at a wide temperature range. In the present case, sensor tests spanned from 0 to 100% mass ratio of ethanol and regular gasoline blends within the -10 to 40 °C temperature range.

Fig. 1 shows a schematic of the impedance transducer. As illustrated, the sensor is basically composed of a pair of coaxial stainless steel electrodes. The ideal annular gap between electrodes was found as function of the mixture bulk resistive sensitivity as well as having in mind to eliminate or to decrease to an acceptable limit the most undesirable capacitance effects (the sensor operates in the resistive range). The set of electrodes is firmly fastened to a PTFE plastic body, where electrical connections are made. Side and top view still pictures of the transducer can be viewed in Fig. 2.

The present type of sensor operates based on the difference of electrical properties between ethanol and gasoline, whose overall behaviour is modelled according to a parallel RC circuit as indicated in Fig. 3. This figure also

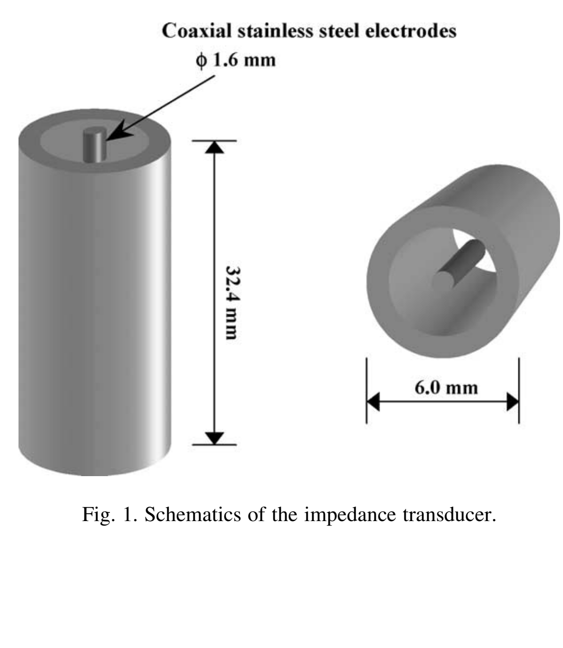

Fig. 1. Schematics of the impedance transducer.

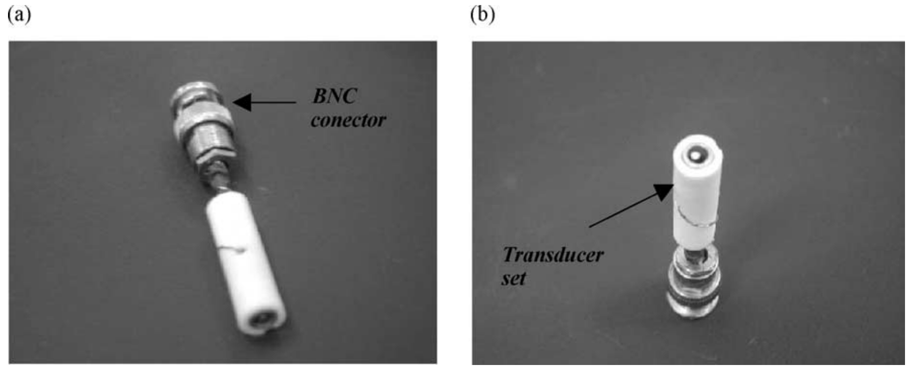

Fig. 2. Still pictures of the electric impedance transducer. (a) Side view; (b) top view.

shows an quite usual circuit used for measuring the transducer overall impedance, Z, formed by a load resistance R in series with the sensor and a power source that applies a voltage V to circuit. According to this elementary model, no electrode effects (electrolysis) take place, except for very low frequencies (order of 10 Hz and below) [7]. The frequency range of the signal applied between the electrodes is closely related to the nature of the electrical impedance to be measured, and consequently to the electrical bulk property of the fuel mixture. Depending on the frequency range of operation, the sensor can indicate the resistive impedance, capacitive impedance, or both. The criteria given by Eq. (1), result from an elementary analysis of the parallel RC model of the transducer. By analysing that equation, it is possible to establish the operating frequency range in which resistive effects dominate

$$\left(\frac{1}{R}\right)^2 \gg (\omega C)^2 \Rightarrow \left(\frac{1}{\omega CR}\right)^2 \gg 1, \quad (1)$$

where ω is the angular frequency, $\omega = 2\pi f$ [rad/s], C is the capacitance of the mixture [F], and f is the power source frequency [Hz] of the applied signal. The transducer and the electrical circuits built for this study was designed to operate in the resistive impedance range.

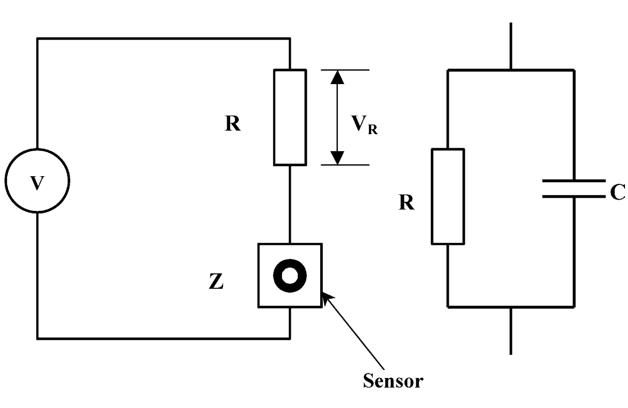

Fig. 3. (a) Basic electric circuit for measuring the fuel mixture impedance. (b) Simple parallel RC model of the transducer.

2.2. The electronic circuit

As seen, the operational frequency range of the voltage source of the electronic circuit is bounded to two limits. Undesirable electrolysis effects on the electrode–fuel interface impose the lower limit, which is relevant to around 10 Hz and below for pure ethanol. Therefore, electrolysis can be avoided by using a voltage power source having a frequency of the order of some kilohertz. The upper limit is set based on the fuel mixture electrical bulk property one wants to work with. Table 1 shows this operating frequency range for the desired main electrical effect, i.e. resistance or capacitance. In this work, the relevant electrical property to be measured was the fuel bulk resistivity. Based on these constraints, an operating frequency from a few kilohertz up to about 400 kHz [7] suffices for conductivity measurements. The chosen working frequency was 20 kHz.

An electronic circuit designed for demodulation and filtering of the applied signal was built according to a version of the project presented in [7]. The signal is generated by an external and very accurate digital signal generator, which provides a 0.2 V/20 kHz sinusoidal wave that is applied to a voltage follower drawing a negligible current from the power source. Next, the signal is driven to the stainless steel coaxial electrodes, which makes an electrical current to cross the fuel mixture filling the space between the electrodes. Some voltage drop across the electrodes is noticed due to the fuel impedance (resistance in this case). An operational amplifier compares the resulting signal with 0 V and drives it to the signal demodulator

Table 1
Dominating electrical property and its operational frequency range for an impedance transducer embebed into ethanol–gasoline blend

Dominating electrical effect	Dimensionless property	Frequency range	Pure ethanol > frequency range (MHz)
Resistivity	K_{0E}/K_M	$f^2 \ll \left(\frac{K_{0E}}{2\pi\varepsilon_E}\right)^2$	$f<0.37$
Capacitance	$\varepsilon_E/\varepsilon_M$	$f^2 \gg \left(\frac{K_{0E}}{2\pi\varepsilon_E}\right)^2$	$f>3.7$

circuit. There, the signal is rectified and the AC signal component is drawn back. The signal is driven to the high-pass filter with a cutting-frequency of 100 Hz. Its important to point out that the mentioned frequency is reasonable for transducer prototypes in laboratory environment conditions but it may not be a good choice for a real fuel injection system control. Finally, the filtered signal is amplified yielding a good sensitivity.

3. Material and methodology

This section exposes the methodology and the material used to obtain the transference function of the electric impedance transducer for ethanol and gasoline blends. The equipment used in this work was a voltage source (± 12.0 Vcc/1.0 A), a digital function generator (0.2 Vpp/20.0 kHz sinusoidal function), a digital multimeter (±0.5 mV), a very accurate thermometer, and a controlled thermostatic bath.

The fuel sample used in this work was hydrous ethanol and ethanol-containing gasoline (25 vol% of non-hydrous ethanol). According to the Brazilian government, the adopted range of ethanol-containing gasoline is 20–25 vol% (true for November/2003). Relevant physical properties of both fuels [8] are presented in Table 2.

The measurement procedure for each sequence was: first to set the voltage source to ±12 Vcc/1.0. A and the digital function generator to a 3.0 Vpp/20 kHz sinusoidal function. The next step was to set-up the mixture to the measurement sequence by weighing each individual fuel using a high precision digital balance to obtain a specified fuel mass ratio β. The fuel mass ratio is giving by

$$\beta = \frac{W_E}{W_M} = \frac{W_E}{W_E + W_G}, \tag{2}$$

where β is the fuel mass ratio, W_E is the ethanol mass [kg], W_G is the gasoline mass [kg], and W_M is the mixture mass [kg]. $\beta=1$ means that the fuel is pure ethanol, while in the other end, $\beta=0$ indicates no ethanol presence (100% gasoline).

The fuel mixture was submitted to an ethylene glycol controlled temperature bath and was kept in the bath up to a complete temperature stabilisation. Also, the temperature was measured before the fuel sample was submitted to tests with a precision thermometer (± 0.1 °C). Next, the sensor was inserted into the fuel blend and vigorously agitated to obtain a uniform fuel mixture without stratification points. The electrical conductivity of that fuel sample mixture was obtained from the electronic circuit output reading.

It is straightforward to show that there exists a direct correlation between the voltage drop and the electrical bulk conductivity according to Eq. (3)

$$\frac{V_{0E}}{V_M} = f\left(\frac{K_{0E}}{K_M}\right), \tag{3}$$

and for flat plate electrodes the expression is

$$\frac{V_{0E}}{V_M} = \frac{K_{0E}}{K_M}, \tag{4}$$

where V_{0E} is the measured voltage of electronic circuit signal for pure ethanol, V_M is the measured voltage of electronic circuit for a given ethanol and gasoline blend, K_{0E} is the electric conductivity for pure ethanol, and K_M is the electric conductivity for the corresponding ethanol and regular gasoline blend. In this way, the voltage drop measured is correlated to the electrical conductivity of the fuels by an obtained transference function, as it is showed and discussed in the next section.

Table 2
Relevant physical properties of each individual fuel tested [8]

Property (at 20°C)	Symbol	Unit	Ethanol	Regular gasoline
Formula	–	–	C_2H_5OH	C_4 to C_{12}
Freezing point	–	°C	−114	−40
Boiling point	–	°C	78	27–225
Density	ρ	[kg/m^3]	809.0	720.0
Electrical conductivity	K	[μS/m]	500	–[a]
Dielectric constant	ε_0	–	24.30	2.00

[a] The electrical conductivity of the gasoline sample used was not known.

4. Results

4.1. Impedance measurements

The first set of experiments was carried out for fuel mass ratios (β) varying from 0 to 1.0 at 20 °C. The data set for relative voltage drop of fuel mixtures, V_{0E}/V_M, are plotted in Fig. 4. Examining that figure, one can notice a well-behaved function having a slightly non-linear correlation between fuel mass ratio, β, and the dimensionless voltage drop, V_{0E}/V_M. The non-linearity of the transference function observed can be attributed to the chemical mixing behaviour of the mixture. A fourth order polynomial was found to be the best curve fitting.

Ethanol is about three times as much best electrical conductor than regular gasoline as indicated by the results of the Fig. 4. At first, this sounded a little erroneous result, considering that hydrocarbons, such as gasoline, are very poor electrical conductors. However, later on it was found that the relatively high-observed electrical conductivity of the tested gasoline was that Brazilian pump gasoline has the presence of non-hydrous ethanol of 25 vol%. In addition to the presence of non-hydrous ethanol in regular gasoline, there is also the presence of additives for increasing gasoline's electrical conductivity for safety reasons (static dissipaters).

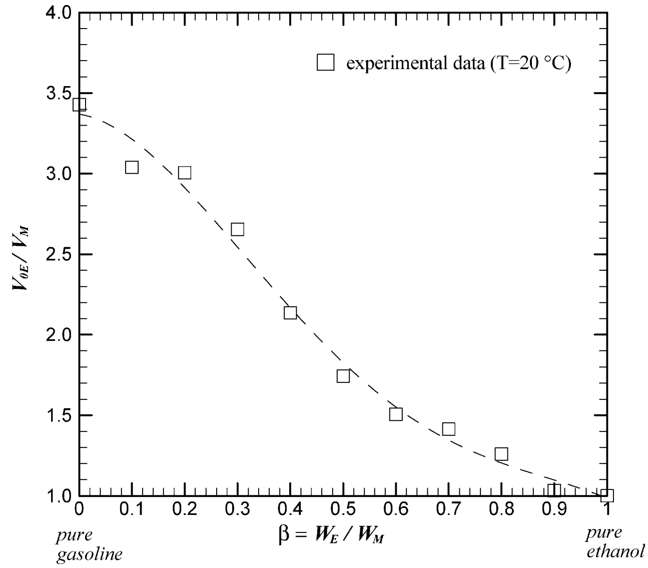

Fig. 4. Transference function for the electrical conductivity of ethanol–gasoline mixture at 20 °C.

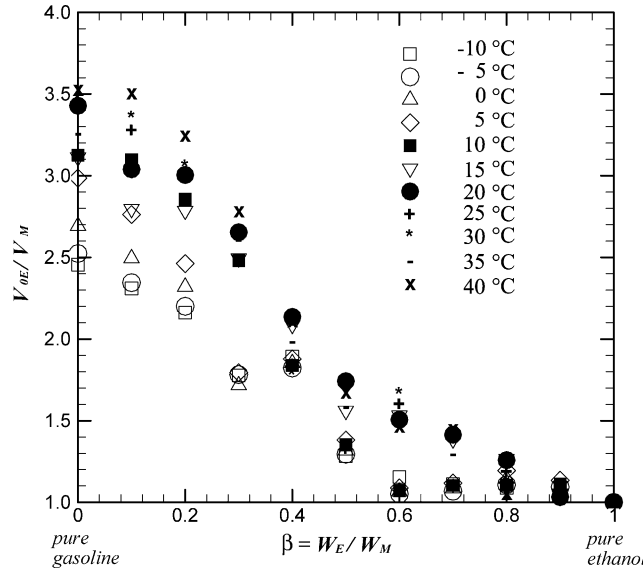

Fig. 5. Temperature influence over the ethanol–gasoline mixture electrical conductivity.

It is important to note that tests were carried out over a simple sample of each fuel. A Brazilian standard for ethanol [8] limits the conductivity to a maximum of 500 μS/m. Also, for different ethanol samples the conductivity may vary significantly and this is the reason why all fuel blends were taken from the same sample of both fuels.

Repeatability tests within the same ethanol–gasoline sample were also carried out. The test results indicated that the sensor signal was quiet stable and reproducible within $\pm 2\%$. However, it is important to stress that the sensor signals were strongly sample-dependent, i.e. a same ethanol–gasoline mass content taken from dissimilar samples yielded to different values, as already pointed out.

4.2. Temperature influence

The present findings are in accordance with Refs. [5,9,10], which inform that the conductivity of hydrocarbon fuels and solvents are generally temperature dependent, primarily due to changes in the mobility of the conducting species related to fuel viscosity effects. Temperature effects should be more drastic when the fuel is treated with static dissipater additives as it occurs with the tested gasoline. According to [5], for an ethanol–gasoline mixture with ethanol concentration less than 5% and above 40%, an increase in temperature increases the conductivity and for samples within this concentration interval, increasing temperature decreases the conductivity. That behaviour is not well known and the literature does not tackle this problem quiet clearly with respect to ethanol–gasoline mixtures. In order to verify the temperature influence over a wide range of temperature, tests were carried out in 5 °C steps starting from −10 to 40 °C. The results are presented in the graphics of Fig. 5.

Close analysis of Fig. 5 allows one to draw some important conclusions. Firstly, the overall polynomial-type behaviour is kept for the entire temperature range tested. Secondly, for the same ethanol content mixture (W_E/W_M), the dimensionless voltage drop (V_{0E}/V_M) decreases, which implies that ethanol and gasoline conductivities do not behave equally with temperature. Ethanol conductivity drops faster than gasoline's as temperature is lowered.

By applying a voltage over the electrodes, a current I is established and, depending on the ability of the fuel or fuel mixture to dissipate electrical charge, it can create a dangerous situation above certain limits. In this work, the maximum measured current was 30 μA, which did not represent any potential risk of accident.

Another important conclusion is that for pure and near pure ethanol condition ($\beta = 1$), a significant influence over temperature-bulk conductivity behaviour is observed, however, for the pure and near pure gasoline condition ($\beta = 0$) the temperature-bulk conductivity relationship does not vary in the same way, i.e. for the pure ethanol, the temperature-conductivity range variation is greater than for pure gasoline. This behaviour can explain data points scattering and the great influence over the dimensionless conductivity, as it can be observed in Fig. 5.

5. Conclusions

The advantages of impedance measurement over other techniques include rapid response time, repeatable measurements, non-destructiveness, and highly adaptable to a wide variety of different applications.

Following the new trend of Brazilian automobile industry to produce flex fuel vehicles, this work shows laboratory tests of a very simple electrical impedance transducer based on measuring the bulk conductivity of ethanol and regular gasoline blends over several mass ratios spanning from 0 (pure ethanol) to 100% (pure regular gasoline) at several temperatures.

It was found a non-linear behaviour between a dimensionless conductivity and fuel composition. The temperature had an important influence over the mixture bulk conductivity and should not be neglected. A limitation for a broader use of this sensor is found on the problem of a large variation of electrical properties in regular fuels (ethanol and gasoline). On the other hand, if the fuels derive from separated tanks so that each fuel conductivity can be obtained independently to adjust the sensor signal as necessary, then the present sensor technique should work perfectly.

Empirical correlation for bulk electrical conductivity and fuel mass ratios can be obtained by using a simple resistive impedance transducer, which opens a new window for detailed investigations.

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