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Gasoline sensor based on piezoelectric lateral electric field excited resonator

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ABSTRACT

It has been shown that by using piezoelectric lateral electric field excited resonators based on X – cut $LiNbO_3$, one can determine the octane number of gasoline. The measured dependence of gasoline permittivity on its octane number has shown that there is an ambiguous connection between pointed parameters. We have demonstrated both theoretically and experimentally that the value of the real part of the electrical impedance on the frequency of parallel resonance uniquely associates with the octane number of gasoline contacting the free side of the resonator. At that the frequency of parallel resonance does not depend on permittivity/octane number of gasoline. An example of determination of the octane number of a mixture of two different samples of gasoline is given.

1. Introduction

It is well known that gasoline presents easily inflammable mixture of light hydrocarbons. It is well known also that octane number of gasoline, which is widely used as fuel for various engines, is a very important parameter. This parameter determinating the capability for detonation is extremely important for ensuring the optimal characteristics of engine operation and its longevity. At the detonation the inflammation of the mixture air – fuel is not descended from spark-plug but from heat of gas mixture which is compressed by the piston. In this case inflammation has explosion character and causes the sharp increase of the temperature and premature wear of the engine. For obtaining the required value of the octane number, special additions are used, which evaporates with time that leads to the change in the octane number. So in a number of cases there is the necessity to check the octane number of gasoline. At present this parameter may be determined by the motor and research methods on the special laboratory stands [1]. There are also attempts to develop methods for determining the impurities of ethanol in gasoline by using terahertz spectroscopy [2]. It is also proposed by using terahertz surface plasmons to recognize different types of gasoline [3]. But these methods may be performed in laboratory conditions with the help of expensive devices with attraction of highly qualified personnel. So the development of a new, cheap sensor for express analysis of the octane number of gasoline represents an urgent problem.

Presently there exist a number of methods for the express determination of gasoline octane number. For example, it is suggested to estimate the octane number of gasoline by measuring its viscosity [4]. But this method was not realized due to the low value of gasoline viscosity. Now there are the meters of octane number such as “TP -131”(China) [5], “OCTANE – IM” (Russia) [6], and “Jeppesen Fuel Tester JS628855” (USA) [7] based on measuring the gasoline permittivity, which uniquely associated with the octane number [8–11]. The main disadvantages of all these methods are the narrow temperature range of operation and the requirement of electrical contacts with gasoline that may lead to its accidental ignition.

There also exist meters of the octane number from series ZX101 [12] based on the measurement of the absorption spectrum of infrared radiation which is unambiguously related to the octane number of gasoline. These meters, however, show a number of significant disadvantages, namely, complicated and unreliable system of spectrum registration due to great amount of switchable filters, high cost, and low accuracy of measurement. An increasing of the measurement accuracy requires at least triply repeated measurements with following averaging-out of the results that leads to inconveniences at the practical application of these devices.

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There exists also a device "Ukrainian Device OKM-2" [13] based on the measurement of the temperature of ignition of the gasoline – air mixture of the certain composition, which determines the octane number. Its disadvantage is a high cost together with a complexity of operation.

There is also a meter based on a self-excited generator, the feedback path of which contains a delay line based on zero order shear horizontal plate mode propagating along Y X–lithium niobate [14]. The container with the gasoline under test is placed on the path of the acoustic wave. It has been shown that the frequency so generated is only associated with the gasoline permittivity which is determined in one's turn by the octane number [8–11]. The disadvantage of this system is the requirement to use very thin plates (~100–200 μm) to ensure the required sensitivity.

There is also the paper devoted to the development of measuring system for real time gasoline octane number determination based on the analysis of the transmission spectrum of a phononic crystal sensor filled with the liquid gasoline blend [15]. This system is characterized by ineferior resolution and the difference between a measured parameter for samples of gasoline with octane numbers 80 and 95 is equal to ~4%. However the measurements demand the consideration of the sample temperature because the velocity of acoustic wave depends on the temperature. At that this system is sufficiently complicated and may be used in laboratory condition.

The aim of this work is to develop a meter for express analysis of the gasoline octane number based on a piezoelectric resonator with lateral electric field. It is well known that such resonator is sensitive to the change in the permittivity of a contacting liquid [16,17].

2. The measurement of the dependence of permittivity of gasoline on its octane number

It is obvious that the development of a sensor for express analysis of the gasoline octane number is connected with the requirement of the measurement of such parameters which are uniquely associated with the octane number. As shown in [8–11,14], gasoline permittivity may be used for this purpose. Table 1 contains the values of permittivity for three different values of the octane number 80, 92, and 95 [9]. We have measured the permittivity for these grades by means of a laboratory made air capacitor with electrodes of 20×20 mm^2 and a gap of 1 mm. Measurements of the capacitance have been taken by using an LCR meter (Agilent 4285) when the capacitor was placed in air or completely immersed in the gasoline samples under test. As the relative permittivity of air equals 1 the sought permittivity of gasoline was determined as the ratio of the capacity values in gasoline and air. The obtained data are also presented in Table 1. The experimental values are in a good agreement with those known from literature. One can see that permittivity increases with increasing the octane number.

3. Theoretical analysis of the parameters of a resonator contacting with different grades of gasoline

The frequency dependencies of both the resistance and reactance of the electrical impedance of the piezoelectric resonator with lateral electric field loaded by gasoline with different values of permittivity have been theoretically calculated by finite element analysis [18]. The scheme of the resonator under theoretical study is shown in Fig. 1a. The geometrical dimensions of all the elements of the resonator and the crystallographic orientations of the plate and electrodes exactly correspond to that which has been previously experimentally studied [19].

Table 1
Averaged values of the relative permittivity from [9] and measured ones for three grades of gasoline.

Octane number	Permittivity from [9]	Measured values of permittivity
80	2.047	2.084
92	2.162	2.148
95	2.211	2.2

The resonator was based on a plate of X – cut lithium niobate, 0.5 mm thick. Electrodes, placed on the lower side of the plate, were oriented so that the lateral electric field was directed along the Y axis. The electrical potentials with given values of amplitude and frequency were applied to the electrodes. The plate orientation and the lateral electric field lead to the excitation of longitudinal acoustic waves in the space between the electrodes, propagating along the normal to the plate and resonating between the sides of the plate [19]. Dimensions of the piezoelectric plate, electrodes and gap were equal to 25, 5, and 3 mm, respectively. In order to suppress parasitic Lamb waves, the region around the electrodes and partially the same electrodes were coated by a damping layer [19]. The width of these regions was equal to 5 and 3 mm, respectively. The upper side of the plate was placed in contact with the gasoline layer, 2 mm thick. The whole system was considered to be embedded in vacuum and the electric field in the vacuum around the resonator was theoretically analyzed inside a circle Γ with a diameter of 100 mm around the center of the resonator (Fig. 1b). The electric potential φ at the boundary of the circle was considered to be zero. A two – dimensional problem was solved in the XY plane, while in the Z direction the structure was considered to be infinite. The method of calculation is presented in detail in [18]. The material constants of lithium niobate (elastic, piezoelectric, dielectric and density) are those of Ref. [20], while those of gasoline (elastic constant and density) are from Ref. [1]. As for the values of the gasoline relative permittivity, the values of 2.0, 2.1, and 2.2, were considered as measured ones for gasoline samples with octane number 80, 92, and 95, respectively. The frequency dependencies of the resistance and reactance of the electrical impedance as calculated for these grades of gasoline are shown in Fig. 2. One can see that the frequency of the parallel resonance is practically independent on the gasoline permittivity and equal about 6.47 MHz, but the maximum value of the resistance decreases with increasing of the gasoline permittivity (Fig. 3).

4. Fabrication of the gasoline sensor and experimental tests

The gasoline octane number sensor, implemented according with the theoretical analysis, is shown in Fig. 4. It consists of X-cut lithium niobate plate, 0.5 mm thick, with 5×10 mm^2 aluminum electrodes placed 3 mm apart on the lower side of the plate. Their orientation was such that the lateral electric field was directed along the Y crystallographic axis. The region around the electrodes and partially the same electrodes were covered by a damping layer for the suppression of parasitic Lamb waves. A metal gasoline container, 25×25 mm^2 wide, was placed on the top of the plate and fixed by a gasoline-resistant epoxy. The dimensions of the container exceeded the size of the damping layer region and did not affect the resonator characteristics.

Fig. 5 shows the frequency dependencies of resistance and reactance of the electrical impedance when the container is empty. The parallel resonance at the frequency of 6.48 MHz is clearly visible, where the intensity of suppressed parasitic oscillations turned out to be significantly lower.

Then, we measured the frequency dependencies of resistance and reactance of the electrical impedance of the sensor loaded by the gasoline with given octane number. These dependencies for values of octane number of 80, 92, and 95 are presented in Fig. 6.