Gasoline Sensor Based on Piezoelectric Lateral Electric Field Resonator

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***Abstract* — This paper presents a method to determine the octane number of gasoline products using a piezoelectric lateral electric field resonator. The dependence of permittivity of the gasoline on its octane number was measured. It has been shown that, for Russian gasoline grades, there is an unique dependence of aforementioned parameters. It has been found theoretically and experimentally that the frequency of the parallel resonance insignificantly changes with the change of the permittivity of gasoline contacting with free surface of the resonator. Our analysis shows that the value of the real part of the electrical impedance on the resonant frequency is unambiguously determined by the octane number of the gasoline. We provide an example of the determination of the octane number of an arbitrary mixture of different gasoline grades. We also consider the temperature of the gasoline sample under study.**

Keywords - octane number of gasoline; relative permittivity; lateral electric field excited piezoresonator; gasoline sensor.

I. INTRODUCTION

Gasoline, which is widely used as engine fuel, represents the inflammable mixture of light hydrocarbons. The most important parameter of gasoline is its octane number, which characterizes its detonation resistance. This parameter is extremely important to ensure the optimal characteristics and durability of a working engine. Detonation is a process of spontaneous inflammation of air-and-fuel mixture not from the spark plug, but from heat of the gas mixture, which is compressed by the piston. In this case, burning has an explosive nature, which leads to the temperature excursion and the premature wear of the engine. In practice, the needed octane number is achieved by using special additives, which may evaporate in time. This process will lead to changes in the octane number of gasoline. So, in a number of cases, one needs to check the octane number of gasoline. At present time, the octane number of gasoline is determined by motor and research methods on special laboratory equipment [1]. These methods are carried out under laboratory conditions, with the help of expensive instrumentation and qualified personnel. Therefore, the development of the sensor for express analysis of octane number of gasoline acquired in fuel stations represents the prospective problem. At present, there exist only several papers devoted to express methods of octane number determination. For example, it is proposed to determinate the octane number of gasoline by measuring its viscosity [2]. But this method has not been put into practice. In our laboratory we develop the sensor based on the self-excited oscillator the feedback of which contains the delay line based on the plate of Y – X lithium niobate with propagating acoustic wave with shear – horizontal polarization [3]. The liquid container with gasoline under study was placed on the path of acoustic wave. It has been shown that the frequency oscillation is unambiguously associated with the permittivity of the gasoline, which, in turn, is determined by its octane number [3]. It is well known that the lateral electric field excited piezo - resonator is sensitive to the change in the properties of contacting liquid [4]. Therefore, the aim of this paper is the development of a sensor for express analysis of gasoline octane number based on the lateral electric field excited resonator. In Section II, we measure the dielectric permittivity of gasoline. In Section III, we describe the fabrication of gasoline sensor. In Section IV, we theoretically analyze the sensor loaded by gasoline. Section V concludes the paper.

II. THE MEASUREMENT OF THE DEPENDENCE OF THE RELATIVE PERMITTIVITY OF GASOLINE ON ITS OCTANE NUMBER

It is obvious that, for the development of a sensor for express analysis of the octane number of gasoline, one needs to know its parameter, which is unambiguously determined by its octane number. As it has been pointed out, this parameter is permittivity. Table 1 contains the region of admissible values of permittivity for three octane numbers: 80, 92, 95 and their averaged values [5].

TABLE I. THE REGIONS OF ADMISSIBLE VALUES OF PERMITTIVITY AND THEIR AVERAGED VALUES TAKEN FROM [5], AND ALSO MEASURED VALUES OF PERMITTIVITY FOR THREE GRADES OF GASOLINE.

Octane number	**80**	**92**	**95**
The regions of admissible values of permittivity [5]	2 – 2.062	2.08 – 2.115	2.145 – 2.205
Averaged values of permittivity [5]	2.031	2.0975	2.175
Measured values of permittivity	2.084	2.148	2.2

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The aforementioned grades of gasoline are standard for Russian market. We have measured the values of permittivity for these grades, which are also presented in Table 1. Below, our method of measurement is described.

For measuring the permittivity, a plane air capacitor with shear dimensions of 20×20 mm^2 and with the gap of 1 mm was fabricated. The capacity of this capacitor in air was measured with the help of the LCR meter 4285A (Agilent). A LCR meter is a piece of electronic test equipment used to measure the inductance (L), capacitance (C), and, resistance (R) of a component. Then, the capacitor was immersed into a sample of the gasoline under study and the capacity was measured again. With the assumption that relative permittivity of the air is equal to 1, the sought permittivity of gasoline was determined as the ratio of capacity in gasoline and capacity in air. The obtained data for the three grades of gasoline is also presented in Table 1. One can see that they are close to the values which are taken from literature. Figure 1 shows the dependence of the measured permittivity of the gasoline on its octane number.

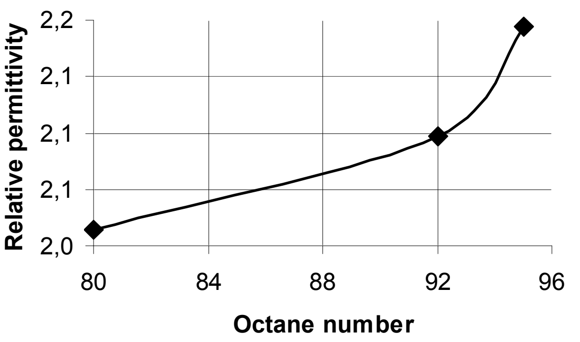

Figure 1. The dependence of measured permittivity of the gasoline on its octane number

It is evident that permittivity of gasoline insignificantly increases with increase of the octane number.

III. FABRICATION OF GASOLINE SENSOR

For fabrication of the gasoline sensor, the piezoelectric resonator with lateral electric field based on the plate of lithium niobate of X cut was used (Figure 2). The plate thickness was equal to 0.5 mm. Two rectangular aluminum electrodes with shear dimensions 5×10 mm^2 and with the gap between them of 3 mm were deposited in vacuum on the lower side of the plate.

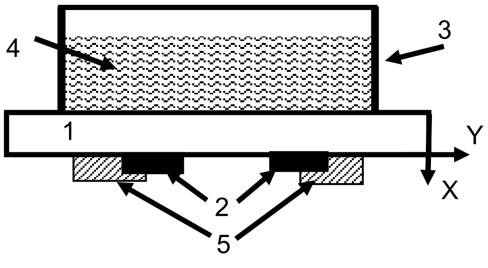

Figure 2. The gasoline sensor: 1 – piezoelectric plate, 2 – electrodes, 3 – liquid container, 4 – gasoline under study, 5 – damping layer.

The orientation of electrodes was chosen in such a way that lateral electric field was directed along crystallographic axis Y. Such orientations of the plate and lateral electric field lead to the excitation of longitudinal acoustic wave in the space between electrodes, which propagates along the normal to the surface and resounds between the sides of the plate [6]. The region around the electrodes was covered by the special damping layer. The metallic liquid container with the shear dimensions of 25 × 25 mm^2 was placed on the upper side of the plate. These dimensions exceeded the sizes of the region of damping layer. The container was fixed to the plate surface with the help of gasoline-resistant epoxy.

Figure 3 shows the frequency dependencies of the real (a) and imaginary (b) parts of the electrical impedance of the resonator with an empty liquid container. One can see that clearly expressed parallel resonance takes place at a frequency of 6.48 MHz. At that close to this frequency, the intensity of suppressed parasitic oscillations is significantly less.

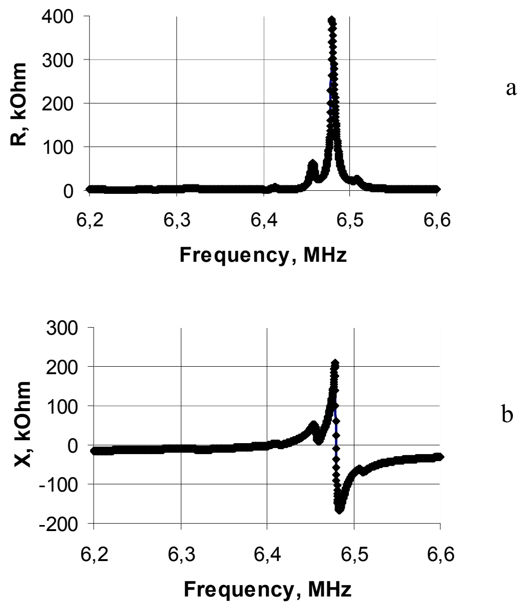

Figure 3. The frequency dependencies of the real (a) and imaginary (b) parts of the electrical impedance of the empty sensor

Then, we measured the frequency dependencies of real and imaginary parts of electrical impedance of the sensor loaded by the gasoline with a given octane number. These dependencies for values of octane numbers of 80, 92, and 95 are presented in Figures 4, 5, and 6, respectively. All measurements were carried out under a laboratory environment with the temperature of 26^{0}C and atmospheric pressure of 99.5 kPa. The detailed analysis has shown that, as an analytical parameter which is unambiguously associated with the octane number of the gasoline we can use the value of the real part of electrical impedance of the sensor on the frequency of parallel resonance. The resonant frequency does not depend on the grade of the gasoline. The dependence of the maximum of real part of the impedance on octane number is presented in Figure 7. This dependence may be used as a calibration curve of the sensor.

We have also carried out the experiment to determine the octane number of the arbitrary mixture of gasoline samples with octane values of 80 and 92. The measured value of the maximum of real part of impedance turns out to be R_{max} = 20.149 kOhm. This data corresponds to the octane number of 82.25.

It is obvious that, in practice, the estimation of the octane number of gasoline must be carried out at different values of environmental temperature and atmospheric pressure. It is well known [7] that the liquid permittivity strongly depends on the temperature and insignificantly changes with the variation in atmosphere pressure. It means that the estimation of octane number of gasoline by measuring its permittivity requires the need of temperature consideration. Our experiments have shown that the frequency of the series resonance does not depend on gasoline octane number (Figure 8) but unambiguously depends on the temperature. So, in the future work, we will measure the dependencies of R_{max} on octane number at various temperature values. In this case, we will obtain the calibration set of curves with the temperature as parameter. The dependence of the frequency of series resonance on the temperature will also be measured.

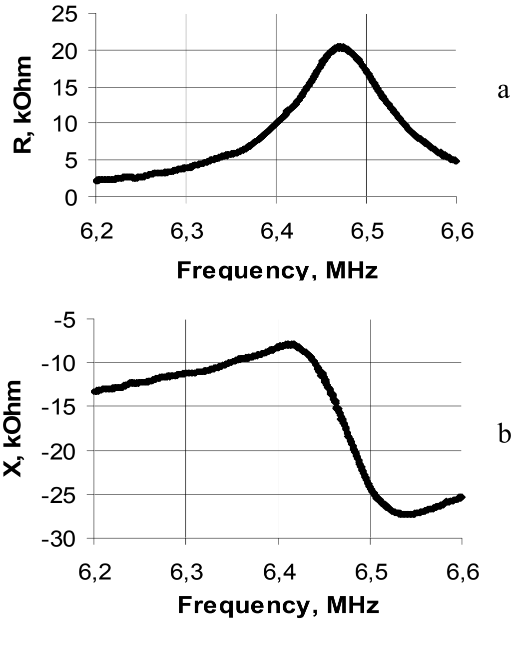

Figure 4. The frequency dependencies of the real (a) and imaginary (b) parts of the electrical impedance for the sensor loaded by gasoline with octane number of 80.

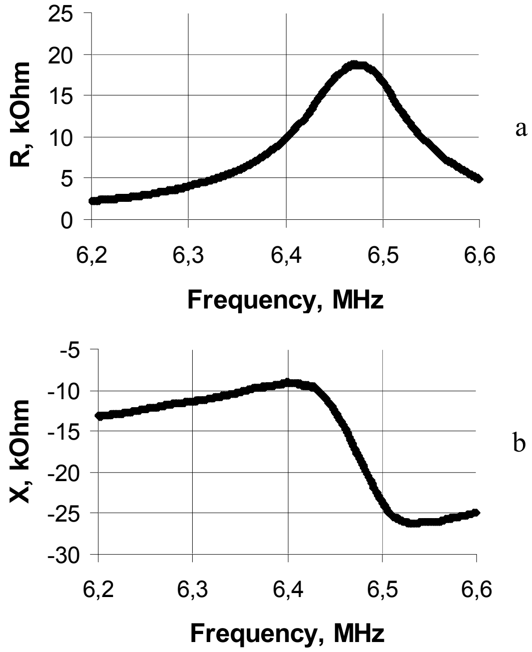

Figure 5. The frequency dependencies of the real (a) and imaginary (b) parts of the electrical impedance for the sensor loaded by gasoline with octane number of 92.

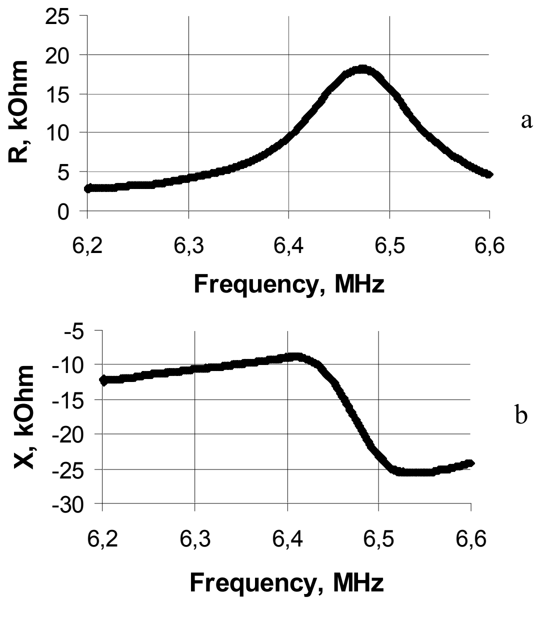

Figure 6. The frequency dependencies of the real (a) and imaginary (b) parts of the electrical impedance for the sensor loaded by gasoline with octane number of 95.

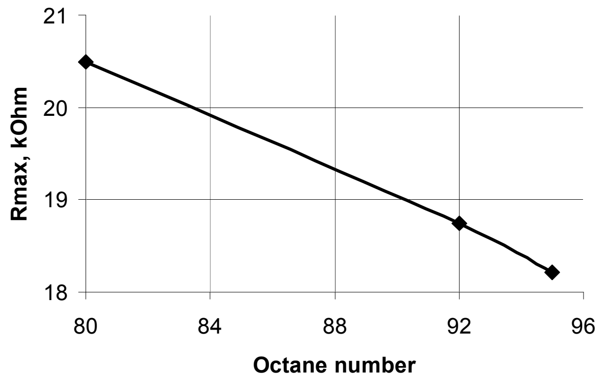

Figure 7. The dependence of the value of real part of the electrical impedance at the frequency of the parallel resonance on octane number of gasoline.

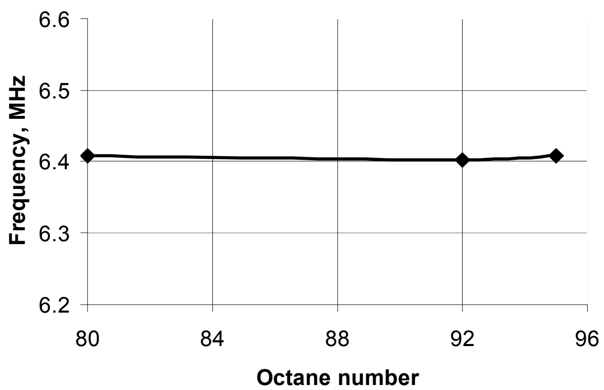

Figure 8. The dependence of the frequency of series resonance on octane number of gasoline.

Therefore, the determination of the octane number of the gasoline considering its temperature will be performed in the following way. For the sample under study, the frequency of the series resonance and the value of R_{max} will be measured. Then, by using the temperature dependence of this frequency, the temperature of the sample will be found. This will allow to choose the corresponding branch on the calibration set of curves and to determine the sought octane number by using the known value of R_{max}.

IV. THEORETICAL ANALYSIS OF REAL AND IMAGINARY PARTS OF RESONATOR LOADED BY VARIOUS GRADES OF GASOLINE

In this work, we also calculated the frequency dependences of real and imaginary parts of the resonator loaded with gasoline samples with different dielectric permittivity.

The theoretical analysis was carried out using the finite-element method [8]. The geometry of the problem is shown in Figure 9.

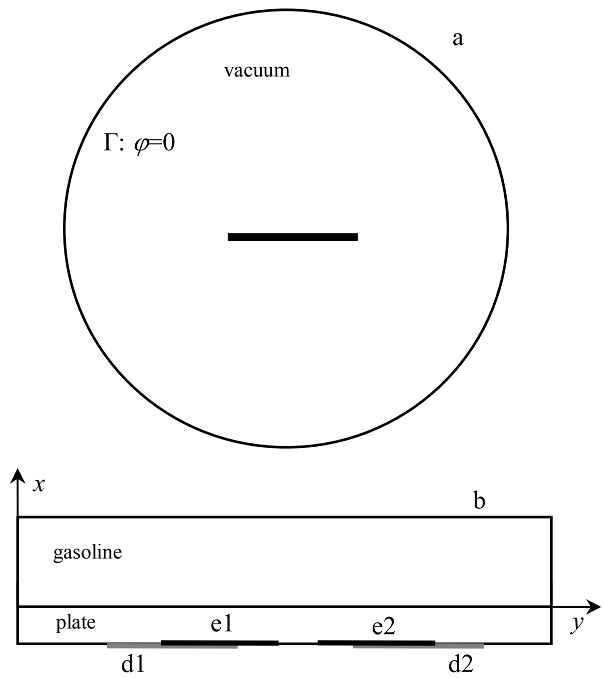

Figure 9. (a) Overview of the region of solution; (b) the central part of the region of solution: the plate of resonator and the gasoline layer, e1, e2 are electrodes, d1, d2 are damping layers.

The geometrical dimensions of all elements of the sensor and crystallographic orientations of a plate and electrodes in the XY plane are accurately equal to the experimental ones. The width of a piezoelectric plate, the electrodes and the gap between them were equal to 25 mm, 5 mm and 3 mm, respectively. The width of the area of a covering around electrodes was equal to 5 mm. The upper side of a plate was contacted with the layer of gasoline of 2 mm thick.

In the direction of the Z axis, the structure was implied to be infinite. All calculations were carried out inside a circle with a diameter of 100 mm. The elastic, piezoelectric and dielectric constants of lithium niobate and its density were taken from [9]. The speed of sound in gasoline and its density were taken from [1]. The relative permittivity of grades of gasoline were assumed to be equal to 2.0, 2.1, and 2.2 respectively. The computed dependencies of real and imaginary parts of electrical impedance for these three grades of gasoline are shown in Figure 10.

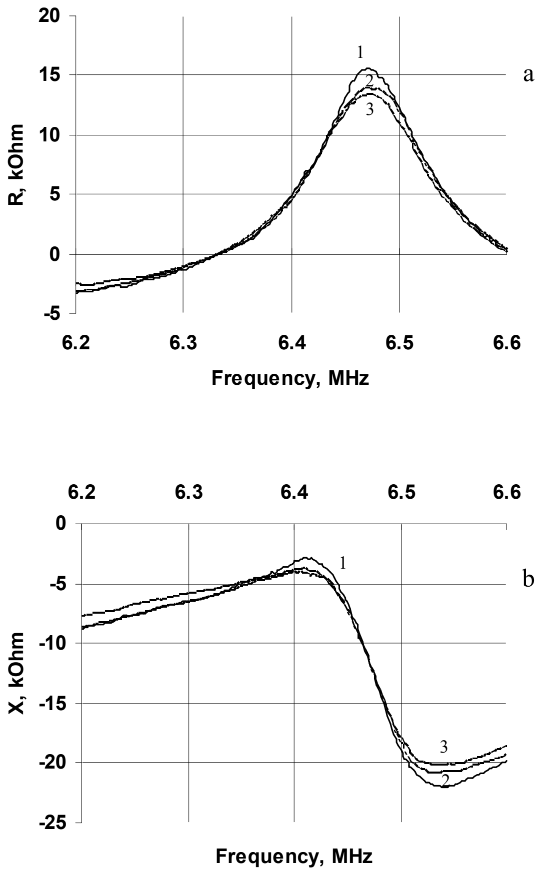

Figure 10. Theoretical frequency dependencies of real (a) and imaginary (b) parts of electrical impedance for permittivity 2.0 (1), 2.1 (2) and 2.2 (3).

So, it is shown that the theory and the experiment are in satisfactory agreement with each other.

V. CONCLUSION

In this paper, we developed a meter to measure the gasoline octane number based on the piezoelectric resonator with lateral electric field. The dependence of the relative permittivity of gasoline on its octane number was experimentally measured. It has been shown that, for Russian gasoline grades, there exists an unique relation of the aforementioned parameters. It has been theoretically and experimentally shown that the frequency of the parallel resonance insignificantly changes with the change in the gasoline permittivity. Analysis has shown that, as an analytical parameter unambiguously tied with gasoline octane number, one can use the value of real part of electrical impedance on the frequency of parallel resonance. An example of the determination of the octane number of an arbitrary mixture of different gasoline grades was given. We also considered the temperatures of the gasoline samples under study. The possibility of the consideration of the temperature of the gasoline sample under study is shown.

ACKNOWLEDGMENT

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