The use of ionization sensors to study the combustion process in spark ignition engines

Victor Smolenskii¹³, Natalya Smolenskaya¹, Nikolay Korneev² and Yuri Prus²

¹Togliatti State University, Togliatti, Belorussskaya st. 14, Russian Federation;
²Gubkin University, Moscow, Leninsky Prospect, 65, Russian Federation

³Email: Viktor.cm@mail.ru

Abstract. The article discusses the use of ionization sensors to study the combustion process in spark ignition engines. The results of an experimental study of the combustion process when operating both on gasoline and gas fuel are presented. Correlating dependences are obtained, which show the possibility of diagnosing the combustion process by the ion current of chemionization. The relationship between the amplitude of the ion current and the composition of the mixture, the speed of flame propagation, and the maximum pressure in the cylinder of the engine is revealed.

1. Introduction

The phenomenon of electrical conductivity in a flame has been known for a long time. The use of ionization sensors to study and monitor the combustion process in power plants with a continuous combustion process is widespread. Research on the use of ionization sensors in spark ignition engines also has a significant history [1,2]. But due to the complexity of the installation of ionization sensors, as well as the speed of the combustion process, its unevenness in time and volume, it is difficult to use them actively [3,4]. Currently, ionization sensors are used to a greater extent for studying the combustion process, including when working on alternative fuels and new ways of organizing the work process [5,6]. The paper shows the influence of the installation site of ionization sensors on the possibility of studying the combustion process.

2. Experimental technique

Experimental studies were carried out on a single-cylinder unit UIT-85 and on a VAZ-2111 engine. Include information about geometrical parameters of engine UIT-85 and engine VAZ-2111 are shown in table 1. The installation diagram of the ionization sensors in the UIT-85 is shown in Figure 1, and for the VAZ-2111 engine in Figure 2. Compressed natural gas (CNG) and gasoline, as well as natural gas with hydrogen additives and gasoline with hydrogen additives, were used as fuel.

The electrical circuit used to measure the electrical conductivity of the flame for the UIT-85 unit when operating on gasoline and gasoline with the addition of hydrogen is shown in figure 3. The power source here was a +9 V. When the UIT-85 was operated on CNG and CNG with hydrogen, the electric circuit depicted in figure 4 was used, where a 360 V DC source was used as a power source, which are obtained by converting alternating current after a voltage regulator of 220 V to DC.

Investigations of the electrical conductivity of the flame in a VAZ engine were carried out using a multi-channel circuit for measuring electrical conductivity of a flame with galvanic isolation (figure 5)
when powered by a 600 V DC source. The increase in voltage at the sensors for measuring the electrical conductivity of the flame from 360 to 600 V is explained by the greater signal stability with increasing voltage in the gap between the sensor electrode and the motor housing [7].

Table 1. Include information about geometrical parameters of experimental facilities.

|                        | UIT-85       | VAZ-2111          |
|------------------------|--------------|-------------------|
| Number of cylinders    | 1            | 4                 |
| Working volume, l      | 0.652        | 1.499             |
| Compression ratio      | 4 – 10 (7 in this paper) | 9.8 (7.5 with ionization sensors) |
| Cylinder diameter, mm  | 85           | 82                |
| Piston stroke, mm      | 115          | 71                |
| Rod Length, mm         | 266          | 121               |
| Rotation frequency, rpm | 600 or 900   | 800 – 6000        |
| Fuel supply            | Gasoline – Carburetor | CNG and Hydrogen – Intake |
|                        | CNG and Hydrogen – Intake | Manifold Injection |
| Ignition               | Spark plug   | Spark plug        |

Figure 1. Scheme of the UIT-85 combustion chamber with ionization sensors installed in it.

Figure 2. Installation diagram of ionization sensors in the VAZ-2111 engine: 1 - ionization sensor under spark plug; 2 - ionization sensor at the exhaust valve; 3 – special plate.

Figure 3. Ion current measurement circuit: 1 – DC Power Supply 9V; 2 – measuring resistor; 3 – oscilloscope; 4 – electrical conductivity sensor.

Figure 4. Galvanically isolated ion current measurement circuit.

Figure 5. Multichannel isolation current measurement circuit.
3. Results and Discussion

Experimental studies on a UIT-85 single-cylinder unit were carried out using gasoline and CNG, as well as adding hydrogen to activate the combustion process (up to 6% for gasoline and up to 15% of the fuel mass for CNG). For example, figure 6 shows the characteristics of the electrical conductivity of the flame when working on CNG, and figure 7 shows the dependence of the amplitude of the ion current on the composition of the mixture with a change in BTDC.

![Figure 6](image1.png)

**Figure 6.** The characteristic of the ion current when working on CNG in the UIT-85 at 900 rpm, 13 BTDC, on 1 ionization sensor 7 mm from the spark plug and on 2 ionization sensors 80 mm.

![Figure 7](image2.png)

**Figure 7.** The dependence of the amplitude of the ion current in UIT-85 on the composition of the mixture with a change in BTDC at 900 rpm.

Let us consider in more detail the results shown in figure 6. A steel electrode located 80 mm from the spark plug at the end of the combustion chamber is identical to the electrodes used in the UIT-85 series of tests (figure 7) when powered by a +9 V galvanic cell. As expected, an increase in voltage from 9 to 360 V increased the stability and magnitude of the signal with the same parameters of the sensor electrode. Comparing the values of the electrical conductivity of the flame obtained on the copper (7 mm from the spark plug) and steel (80 mm from the spark plug) electrodes, one can note large values of the electrical conductivity on the electrode at the spark plug. But the electrode at the spark plug has a much larger contact area with the flame front, since it, with the same diameter, protrudes by 4 mm, and the steel electrode by 0.3 mm. A change in the carbon fraction in the flame front by increasing the hydrogen fraction in gas fuel initially leads to a slowdown in the growth of the electrical conductivity of the flame in the installation zone of the second sensor, and then to its decrease. This is due to the fact that, as shown by a number of studies [1, 8–10], chemionization in the combustion zone of hydrocarbon fuel is largely determined by CHO+ and C3H3+ ions. Therefore, the results obtained are consistent with known data, where it is shown that a decrease in the content of carbon in the fuel reduces the electrical conductivity of the flame. Although the intensity of the course of the combustion process itself, as occurs with the addition of hydrogen, increases. At the same time, an increase in the proportion of hydrogen in gas fuel (CNG + H2) increases the conductivity characteristics of the spark plug in the zone of formation of a stable burning zone. This reflects the fact of a higher activation energy for initiating the combustion process of natural gas compared to gasoline, and even more so with hydrogen. Therefore, hydrogen increases the combustion rate and forms a stable combustion zone at high flame front temperatures [11], which is reflected in the increase in electrical conductivity at the first sensor.
Looking at figure 7, it can be seen that the signal amplitude at ionization sensor 2 increases with the addition of hydrogen and an increase in BTDC. This is due to the flow of the combustion process in the area of the ionization sensor 2 with a smaller volume. The presented dependences of the signal amplitude on the ionization sensor 2 when operating on gasoline and gasoline with hydrogen additives have a distinct correlation with the composition of the mixture and the conditions of the combustion process. This is perfectly illustrated by the dependences of the amplitude of the ion current on the maximum pressure (figure 8a) and the flame front propagation velocity (figure 8b) with varying compression ratio, BTDC, and mixture composition.

![Figure 8](image)

**Figure 8.** The relationship of the amplitude of the ion current with the characteristics of the course of the combustion process in UIT-85: (a) the relationship of the amplitude of the ion current with maximum pressure; (b) the relationship of the amplitude of the ion current with the average propagation velocity of the flame front.

The flame conductivity characteristics of the VAZ-2111 engine were studied using a special plate with ionization sensors (figure 2) and an ion current measurement system (figure 5). A direct current source of 600 V was used. The investigated operating mode was idle at a frequency of 880 rpm according to the standard calibrations of the controller. In this mode, the maximum unevenness of the working process is observed with a significant content of residual gases. These combustion conditions reduce the intensity of chemical reactions in the flame front, which is reflected in the form of a decrease in the amplitude of the ion current, both on the sensors at the spark plug and on the sensors located at the exhaust valve. CNG (figure 9a) and gasoline (figure 9b) were used as fuel. Figure 9 shows a picture of the signals recorded by the oscilloscope, namely, the moment of spark discharge, indicator pressure, the electrical conductivity of the flame on the sensor 15 mm from the spark plug and the electrical conductivity of the flame on the sensor 45 mm from the spark plug. Analysis of the flame electrical conductivity signals showed a clear electrical conductivity signal on both sensors, despite the difficult combustion conditions of natural gas and gasoline at idle. Let us compare the conductivity characteristics shown in figure 9 when working on CNG and gasoline at the same BTDC of 35 deg. and stoichiometric composition of the mixture. When working on gasoline, the flame front propagates much faster in the initial phase of combustion [12,13]. In this connection, the flame front reaches the electrode under the spark plugs at the compression stroke, and when working on CNG in the region of the top dead center (TDC), which is reflected in the larger value of the electrical conductivity of the flame. At the same time, due to the faster combustion of gasoline, compared with CNG, the flame front also earlier reaches the second electrode at the exhaust valve. This corresponds
to large values of pressure and temperature due to combustion in a smaller volume, thereby increasing the number and density of ions in the flame front, which increases its electrical conductivity.

![Image](image1.png)

**Figure 9.** Type of ion current signal for the VAZ-2111 engine at idle at a speed of 880 rpm: (a) when operating on CNG; (b) when operating on gasoline.

![Image](image2.png)

**Figure 10.** The relationship of the amplitude of the ion current with the characteristics of the combustion process in the engine at a compression ratio of 7.5: (a) the relationship of the amplitude of the ion current with the composition of the mixture; (b) the relationship of the amplitude of the ion current with maximum pressure.

Let us further analyze the amplitude of the ion current when operating on gasoline and gasoline with the addition of 0.02 kg/h of hydrogen. Figure 10 shows the presence of a correlation of the amplitude of the ion current with the composition of the mixture and the maximum pressure in the combustion process, even with significant unevenness of the flow of the working process at idle. Figure 10a shows that the dependence of the amplitude of the ion current on the composition of the mixture has a large correlation for the second sensor installed at the exhaust valve. This is confirmed by the correlation of the amplitude of the ion current from 2 sensors with maximum pressure (figure 10b). The results obtained show the value of using the phenomenon of electrical conductivity of the flame to study the combustion process in spark ignition engines [14]. It is shown that the location of the ionization sensors significantly affects the correlation of the received signal with the characteristics
of the course of the combustion process. Ignition conditions are well monitored by a sensor located in the area of the spark plug. Pressure characteristics are better correlated when installing the sensor in a more remote area of the combustion chamber. The data obtained show that the flame conductivity characteristics reflect the local state of the combustion process.

4. Conclusion
1. The difference in the characteristics of the ion current when working on gasoline and CNG was revealed. It is shown that the amplitude of the ion current reflects the composition of the fuel-air mixture and depends on the type of fuel, the coefficient of excess air, the amount of residual gases.
2. The correlation of the amplitude of the ion current with the mixture composition, maximum pressure, ignition timing, compression ratio and flame propagation rate is shown.

References
[1] Hellring M and Holmberg U 2000 An ion current based peak-finding algorithm for pressure peak position estimation SAE 01 2829
[2] Gao Z, Wu X, Man C, Meng X and Huang Z 2012 Applied Thermal Engineering 33(34) 15–23
[3] Collings N and Bray K 1991 Endeavour 15 10–2
[4] Tong S, Yang Z, He X, Deng J, Wu Z and Li L 2017 Knock and pre-ignition detection using ion current signal on a boosted gasoline engine SAE 01 0792
[5] Kusuhara T, Shinkai T, Yoshida K and Langley D 2017 Development on internal EGR feedback control based on ion current SAE 2017-01-0793
[6] Dong G Y, Chen Y L, Wu Z J, Li L G and Dibble R 2015 Proc Combust Inst 35 3097–105
[7] Smolenskaya N et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 450 032017
[8] Malaczynski G, Roth G and Johnson D 2013 Ion-sense-based real-time combustion sensing for closed loop engine control SAE Int. 01 0354
[9] Docquier N and Candel S 2002 Prog Energy Combust Sci 28 107–50
[10] Martínez-Morales J D, Palacios-Hernández E R and Velázquez-Carrillo G A 2014 J Mech Sci Technol 28 2417–27
[11] Smolenskaya N M and Korneev N V 2017 IOP Conf. Ser.: Earth Environ. Sci. 66 012016
[12] Lagana A A M, Lima L L, Justo J F, Arruda B A and Santos M M 2018 Fuel 227 469–77
[13] Fiedkiewicz L, Pielecha I and Wisłocki K 2017 Combustion Engines 171(4) 196-200
[14] Ashok B, Ashok S D and Kumar C R 2016 Ann Rev Control 41 94–118