Device for measuring the electrical conductivity of a flame for the diagnosis of the combustion process in an ICE with spark ignition

Natalya Smolenskaya¹, Igor Bobrovskij¹²³, Victor Smolenskii¹, Nikolaj Bobrovskij¹ and Aleksey Lukyanov³

¹ Togliatti State University, Togliatti, Russian Federation
² Samara Scientific Center of the Russian Academy of Sciences, Samara, Russian Federation
³ Email: bobri@yandex.ru

Abstract. In this article the influence of the measurement system, such as material of the sensor electrodes, their location and their contact area with the combustion zone and also the characteristics of the electric field on the character of the flame's electrical conductivity signal are considered. The impact of various engine performance parameters on the electrical conductivity of the flame was evaluated and the interrelation of the electrical conductivity characteristics with propagation conditions of the flame front in the sensors' location area is shown. The influence of the fuel composition on the propagation conditions of the flame front and on its electrical conductivity is shown. Critical analysis of problems and questions of using the flame conductivity measurement system for the combustion process diagnostics in an ICE with spark ignition is carried out.

1. Introduction
The combustion process is a complex and often stochastic process and has its own irregularity. At the same time, obtaining a low-toxic combustion process is often possible in a small range of mixture compositions and certain temperatures of the combustion process and cooling temperatures of the combustion products. To fulfill this goal, the necessary conditions for combustion must be clearly maintained. In this case direct monitoring of the combustion process is complicated by high temperatures (2500 – 3000 K) and high pressures (5 – 20 MPa) at a high process speed (10 – 200 m/s), which makes it difficult to use many sensors for direct monitoring of the process. One of the determinative characteristics of combustion process is propagation of the flame front. It has been known for a long time that the flame front is a rapid oxidation process similar to plasma [1, 2]. It is also known that the plasma is an electrically conductive environment. Therefore, more than 80 years ago, active investigations of the electrical conductivity of a flame began in order to better understand the physics of the combustion process and to obtain a tool for diagnosing the combustion process in power plants [3 – 6]. Nowadays, there are successfully used prototypes of combustion control devices based on the flame's electrical conductivity phenomenon [7 – 13]. They are used in furnaces to maintain a low-toxic operating mode. Also they are used in gas turbine engines to control the flow of the combustion process and the possibility of engine boosting when operating at high altitudes [14]. The phenomenon of electrical conductivity of the flame has found application in other scopes, where the combustion process is quite stationary or continuous. The attempts to use the electrical conductivity of a flame for automobile
engines' control have been known for a long time. However, the combustion process in ICE is complicated by the movement of the piston, the constant change in the rate of heat generation in time, the high turbulence of the flow, and the short time of the whole combustion process (from 10 ms at low speeds to 1 ms at maximum engine speeds). It leads to the complexity of obtaining the qualitative signal of the flame's electrical conductivity characteristics, which provides a reliable picture of the combustion process [15 – 20]. Therefore, in this article, we will consider some issues of sensor design, their power supply and interpretation of the received signals for control and diagnose the combustion process of piston ICEs with spark ignition (SI).

2. Experimental technique
Experimental studies were carried out on a single-cylinder UIT-85 installation (figure 1a) and on a VAZ-2111 engine (figure 2). Include information about the geometric parameters of the engine UIT-85: number of cylinders – 1; working volume – 0.652 l; compression ratio – 7; diameter of the cylinder – 85 mm; piston stroke – 115 mm; length of connecting rod – 266 mm; rotational speed – 600 or 900 rpm; ignition – spark plug. Include information about the geometric parameters of engine VAZ-2111: number of cylinders – 4; working volume – 1.499 l; compression ratio – 9.8; diameter of the cylinder – 82 mm; piston stroke – 71 mm; length of connecting rod – 121 mm; rotational speed - 800 - 6000 rpm; ignition – spark plug.

![Figure 1. The UIT-85 plant (a) and (b) sensors arrangement in the combustion chamber.](image)

![Figure 2. The VAZ-2111 engine.](image)
Steel or copper rods with 1 mm thickness were used as the sensors for studying the electrical conductivity of the flame in UIT-85 plant. They were installed into the ceramic insulator, the scheme of its arrangement is shown in Figure 1b. Aluminum rods with 1.2 mm thickness with an electrically insulating layer were installed in the VAZ-2111 engine (microarc oxidation with micro additives SiO2 [21]) was used as well as steel rods with 1 mm thickness, which were inserted into the ceramic insulator. The general view of the sensors for testing of the flame's electrical conductivity used in UIT-85 plant is shown in Figure 3, and for the VAZ engine in Figure 4. Compressed natural gas (CNG) and gasoline were used as fuel in UIT-85 [22]. CNG and gasoline were used in the VAZ-2111 engine [23].

Figure 3. General view of the sensors for testing the electrical conductivity of the flame in UIT-85 plant: a) copper electrode beside the spark plug; b) steel electrode in an adapter with a pressure sensor; c) five steel electrodes in one housing.

Figure 4. General view of the sensors for testing the electrical conductivity of the flame in VAZ-2111 engine: a) steel sensors in a ceramic shell; b) aluminum sensors in the cylinder head; c) aluminum sensors in a special plate.

The transition from steel electrodes in the ceramic insulator to aluminum ones with an electrically insulating oxide layer is associated with the need to reduce the influence on the cylinder head from the sensors installed in it, and in order to increase reliability of the construction. The transition to steel electrodes made it possible to reduce the loads from thermal stresses. Oxidation allowed to reduce the diameter of the hole from 2.5 to 1.3 mm which increased the efficiency of this measurement system.

3. Results and discussion

Regarding the results obtained on a single-cylinder UIT-85 with a compression ratio of 7 and a rotation frequency of 900 rpm, Figure 5 shows the results of comparing the electrical conductivity of the flame on the first electrode (80 mm from the spark plug) of the five-electrode sensor when working on gasoline and changing the polarity of the electrode's voltage from +9 to -9 V. The electrical conductivity of the flame reflects the change in ignition timing due to the fact that at a greater ignition timing the flame approaches the sensor electrode with a smaller volume and higher pressure, which increases the density of particles in the flame front and consequently increases the electrical conductivity. The same can be applied to the composition of the mixture, i.e. mixtures with a higher combustion rate have a greater electrical conductivity. The results for all five sensors are identical. Therefore, the electrical conductivity for the spark ignition closest to the spark plug is shown as example. The next step is to estimate the
polarity effect on the electrical conductivity characteristics in the combustion chamber of a piston IC with spark ignition. The engine housing is repeatedly grounded, through supports, through the electric motor, through the ground from a special wire from the cylinder block to the metal rod dug into the ground. Therefore, applying a positive charge to the electrode cause ionic conductivity, and applying a negative charge to the electrode cause electronic conductivity. The number of electrons in the flame front is greater than the number of ions. Therefore, the electrical conductivity is more than 2 times greater than the electrical conductivity when supplying a negative charge to the electrode. At the same time, due to the work with compression ratio of 7, the temperature behind the flame front is usually below the temperature of the thermal ionization, which indicates that the electrical conductivity signal is zero. And in the case of a negative voltage on the electrodes, in all cases there is an electrical conductivity of the electrons behind the flame front, which are of a thermal nature.

The disadvantages of a negative voltage application for evaluating the electrical conductivity of a flame are: a greater signal noise; an active display of the spark discharge characteristics; the difficulty in fixing the end of combustion in the sensor location area. At the same time, the use of a galvanic cell with a voltage of +9V on the electrode gave a low signal level when working on over-rich or lean mixtures, where the combustion process is difficult.

![Figure 5](image1.png)

**Figure 5.** The electrical conductivity of the flame on the first electrode of the five-electrode sensor when working on gasoline and changing the polarity of the electrode's voltage from +9 to -9 V.

![Figure 6](image2.png)

**Figure 6.** The flame's electrical conductivity of the 6 mm under the spark plugs (a) and (b) at a distance of 44 mm from the spark plug in the VAZ-2111 engine when working on gasoline at a rotation speed of 1620 rpm, a load of 20% and power supply from the galvanic cell +9V.
When the VAZ engine (the sensor circuit is shown in Figure 6a) was loaded at 20% with the stoichiometric mixture composition, only the signal from the sensor at the spark plug was acceptable. The signal from sensor beside the exhaust valve was weak, and with any deterioration in the combustion process, it practically merged with the noise. Comparing the characteristics of flame conduction signals with identical sensors located at the spark plug and at the exhaust valve, there are large values of the electrical conductivity at the sensor near the spark plug. This can be explained by the fact that the flame front near the spark plug cools down from plasma state when ignited by an electric spark during the formation of a stable combustion source and has a temperature, and hence the electrical conductivity higher than the flame front electrical conductivity in the zone of the exhaust valve at the end of the combustion process at expansion.

Analysis of the influence of the electrode material on the electrical conductivity sensor on the characteristics of the signal obtained showed that the electrical conductivity of steel, aluminum and copper is many times greater than the electrical conductivity of the flame. Consequently, the sensor electrode material does not affect the character of the electrical conductivity signal, or its effect is minimal and corresponds to the level of experimental error. From the external environment measurement system include the following significant factors that have a significant effect on the electrical conductivity characteristics of the flame. The first characteristic is the electrode contact area with the flame front. The larger the area of contact, the more stable and intensive the recorded signal. The second characteristic is the location of the electrode. In the area of the spark plug, the signal is stronger, as the distance from the spark plug, and especially in the afterburning zone, the signal weakens, thereby reflecting the decrease in the intensity of the combustion process. The third characteristic is the polarity of the voltage applied to the electrode. That is, by feeding a negative charge to the electrode, we can several times reduce the electric field strength to obtain a stable signal, thereby reducing our effect on the course of the combustion process. However, this approach requires additional studies, since the vast majority of studies have been conducted with a positively charged electrode, and studies with a negatively charged electrode are very small to obtain a reliable and complete picture. So it is possible to obtain a stable signal with a negative voltage at the electrode of 9 or 12 V, which can be done without significant costs on board the car.

4. Conclusions

In this article, an approach is proposed to assess the possibility of diagnosing the combustion process in an ICE with spark ignition by measuring the electrical conductivity of a flame. Proposed analysis of the factors influencing the stability and accuracy of diagnostics. The influence of the propagation characteristics of the flame front in its electrical parameters. Revealed no significant effect of the material of the sensor electrode on the characteristics of the resulting signal.

It was revealed that by using electronic conductivity instead of ionic increased stability of the resulting signals and expands the signal reception area of the sensor in the electrical conductivity combustion zone where thermal ionization is not yet fixed.

References
[1] VanDyne E A, Burcmyer C L, Wahl A M and Funaioli A E, Misfire Detection from Ionization Feedback Utilizing the Smartfire Plazma Ignition Tecnology SAE 2000-01-1377
[2] Vressner A 2007 Studies on the load range of an HCCI engine using in-cylinder pressure, ion current and optical diagnostics Doctoral thesis
[3] Mott-Smith H and Langmuir I 1926 Phys. Rev. 28(5) 727
[4] Eindinder H J 1937 The Journal of Chem. Phys. 26(4)
[5] Shuler K E and Weber J 1934 Journal of Chem.Phys. 22(3)
[6] Calcote H F and King I 1955 Studies of ionization in flames by means of langmuir probes Technical report
[7] Upadhay D and Rizzoni G AFR Control on a Single Cylinder Engine Uzing the Ionizaition
Current SAE 980203

[8] Hellring M, Munter T, Rögnvaldsson T, Wikström N, Carlsson C, Larsson M and Nyton J Robust AFR Estimation Using Ion Current and Neural Networks SAE 1999-01-1161

[9] Saitzkoff A, Reinmann R, Mauss F and Glavmo M In-Cylinder Pressure Measurements Using the Sparg Plug as an Ionization Sensor SAE 970857

[10] Auzins J, Johansson H and Nyton J Ion-Gap Sense in Misfire Detection, Knock, and Engine Control SAE 950004

[11] Vressner A, Strundh P, Hultqvist A, Tuntstal P and Johansson B Multiple Point Ion Current Diagnostics in an HCCI Engine SAE 2004-01-0934

[12] Strand P, Christensen M and Vressner A 2003 Ion current sensing for HCCI combustion feedback SAE Paper 2003-01-3216

[13] Bruce M 2000 Estimation of the EGR rate in a GDI engine working in stratified mode using the ionization current Doctoral thesis

[14] Egorov A G, Migalin K V and Shaikin A P 1989 Experimental study of ignition and stabilization of powder aluminum flame in combustion chamber with sudden expansion, Soviet Aeronautics (English translation of Izvestiya VUZ, Aviatsionnaya Tekhnika)

[15] Wilstermann H, Greiner A, Hohner P, Kemmler R, Maly R R and Shenk J Ignition System Integrated AC Ion Current Sensing for Robust and Reliable Online Engine Control SAE 2000-01-0553

[16] Eriksson L 1999 Spark Advance Modeling and Control Doctoral thesis

[17] Malaczynski G, Roth G and Johnson D 2013 Ion-Sense-Based Real-Time Combustion Sensing for Closed Loop Engine Control SAE Int. J. Engines 6(1)

[18] Andersson I 2002 Cylinder Pressure and ionization current modeling for spark ignited engines Doctoral thesis

[19] Henein N, Bryzik W and Gupta A 2010 Characteristics of ion current signals in compression ignition and spark ignition engines SAE Int. 3(1) 260-81

[20] Panousakis D, Gazis A, Patterson J and Chen R 2006 Analysis of SI combustion diagnostics method using ion-current sensing techniques SAE Paper 2006-01-1345

[21] Krishtal M M, Polunin A V, Ivashin P V, Borgardt E D and Yasniov I S 2016 Changes in the phase composition of oxide layers produced by microarc oxidation on Al–Si and Mg alloys induced by additions of SiO2 nanoparticles to the electrolyte, Doklady Physical Chemistry

[22] Smolenskaya N M and Korneev V N 2017 IOP Conf. Ser.: Earth Environ. Sci. 66 012016

[23] Smolenskaya N M, Smolenskii V V and Bobrovskij I 2017 IOP Conf. Ser.: Earth Environ. Sci. 50 012016