The electrical conductivity of the flame front, as a characteristic of the rate of heat release and composition of gas fuel in SI engines

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Abstract: The paper considers the possibility of using the electrical conductivity of the flame front as a characteristic of the rate of heat release and composition of gas fuel in a SI engine. Based on the analysis of the experimental data, the dependences of the parameters of the electrical conductivity of the flame front on the rate of heat release are obtained with the variation of the chemical activity of the gas fuel in a SI engine. The influence of the composition of the mixture and the effect of the amount of added hydrogen on the increase in the rate of heat release and, consequently, on the increase in the electrical conductivity of the flame. The obtained dependences will allow to increase the efficiency and reduce the toxicity of the SI engine operation during the regulation of the working process by ionization sensors.

1. Introduction
The phenomenon of the electrical conductivity of the flame front is characterized by the presence in the combustion process of a large number of ionized molecules. So in the combustion zone the following are the main ions: CH$_3^+$, CHO$^+$, OH$^+$, H$^+$, H$_3$O$^+$ [1 – 5]. Therefore, the flame front is capable of conducting an electric current. In this case, the characteristic of electrical conductivity is determined, first of all, by the density of ions in the zone of the ionization sensor. On the basis of this, many researchers suggest that the characteristics of the electrical conductivity of the flame front allow us to more accurately estimate the parameters of the flow of the working process. Therefore, it is possible to implement a system for controlling the operation of the engine by ionization sensors [6]. This control system will allow to more accurately maintain efficient engine operating modes while reducing toxicity. This is necessary with further tightening of toxicity standards and active introduction of gas fuel. As shown by numerous studies and projects that have been practically realized, natural gas is called environmentally friendly fuel with the addition of a chemical activator of combustion in the form of hydrogen.

For this purpose, this work is an extension of knowledge about the possibility of estimating the rate of heat release from the characteristics of the electrical conductivity of the flame front near the spark plug in the initial phase of combustion and remotely from it in the main combustion phase.

2. Experimental technique
Experimental studies were carried out on a single-cylinder UIT-85 unit. Geometric parameters of the engine: the cylinder capacity is 0.652 liters, the cylinder diameter is 85 mm, the piston stroke is 115 mm, the compression ratio is 7. The electric motor keeps the revolutions constant, uniformity of the fuel-air mixture is provided by heating the intake manifold.

Registration of the movement of the flame front inside the UIT-85 cylinder (Figure 1) was carried out by ionization sensors. The ionization sensor 2 was located near the spark plug 1 (Figure 2a), and the ionization sensor 3 was installed in an adapter with a pressure sensor 4 (Figure 2b). This arrangement of the ionization sensors makes it possible to evaluate the propagation parameters of the flame front in the initial and final phases of combustion [7, 8].
Figure 1 – The diagram of the combustion chamber of the UIT-85 unit, where 1 – spark plug; 2 – ionization sensor; 3 – ionization sensor; 4 – pressure sensor

Figure 2 – The applied ionization sensors: (a) ionization sensor 1, installed next to spark plugs; (b) ionization sensor 2, installed next to the pressure sensor

The installation was performed at a fixed ignition timing angle of 13 BTDC and a rotation speed of 909 min\(^{-1}\). The experiment was based on parallel recording of signals by a multichannel analog digital converter L-783M L-CARD. Signals were recorded from the following sensors: ionization, spark ignition, the position of the crankshaft, the pressure in the engine cylinder, the mass flow of air. The toxicity and the coefficient of excess air (\(\alpha\)) were determined from the gas analyzer and the lambda sensor LSU 4.9. Natural gas and hydrogen were fed separately into the intake manifold for the carburetor, the mass flow rate of gas was determined from the calibrated duty ratio of the injectors.

3. **Results and Discussion**

To determine the possibility of estimating the rate of heat release from the electrical conductivity of the flame, experimental data were processed. The characteristics of the change in work and internal energy in the elementary section of the indicator diagram were found to be 0.27 degrees of the angle of rotation. The change in the work and internal energy at the elementary section characterizes the rate of active heat release:

\[
\Delta Q_{\text{act}} = \Delta A + \Delta U = p\Delta V + \frac{C_v}{Z_r(p,T) \cdot R_{\mu}} \cdot V\Delta p,
\]

where \(\Delta A\) – the elementary work; \(\Delta U\) – the change in internal energy in an elementary area; \(p\) – the average pressure on the elementary section; \(\Delta V\) – the volume change in the elementary section; \(C_v\) – the average molar heat capacity at a constant volume on an elementary section; \(Z_r(p,T)\) – the real gas compressibility factor; \(R_{\mu}\) – the universal gas constant; \(V\) – the average volume on an elementary site; \(\Delta p\) – the change in pressure on an elementary section.
Figure 3 – The change in the basic thermodynamic parameters of the cycle characterizing the rate of heat release and the electrical conductivity of the flame for UIT-85 when working on CNG = 85%, H₂ = 15%.

As a result of the thermodynamic analysis of the indicator diagrams [9 – 12], the characteristics of the amount of actively evolved heat in the combustion process. Where $Q_{\text{act}}$ is the sum of the change in work and internal energy from the start of the combustion process to its completion. It characterizes the amount of actively released energy from the moment of ignition during the entire combustion process. The results of the influence of the composition of the mixture, with a variation in the fraction of hydrogen in the fuel, on the amount of heat released are shown in Figures 4a, 5a, 6a, 7a. In these figures, we see that an increase in the proportion of hydrogen increases the rate of heat release, and, consequently, the efficiency of supply of heat. The conductivity characteristics corresponding to these regimes are given in the Figures 4b, 5b, 6b, 7b. In these figures, we see that with an increase in the proportion of hydrogen, the signal intensity and its stability increase. This is observed both on the sensor at the spark plug and on the ionization sensor 2 located in the part of the combustion chamber remote from the spark plug.

Figure 4 – The effect of the excess air factor for the composition of the mixture CNG = 85%, H₂ = 15%: (a) on the amount of actively released heat in the combustion process; (b) on the electrical conductivity of the flame.
Figure 5 – The effect of the excess air factor for the composition of the mixture CNG = 90%, \( \text{H}_2 = 10\% \): (a) on the amount of actively released heat in the combustion process; (b) on the electrical conductivity of the flame.

Figure 6 – The effect of the excess air factor for the composition of the mixture CNG = 95%, \( \text{H}_2 = 5\% \): (a) on the amount of actively released heat in the combustion process; (b) on the electrical conductivity of the flame.

Figure 7 – The effect of the excess air factor for the composition of the mixture CNG = 100%; (a) on the amount of actively released heat in the combustion process; (b) on the electrical conductivity of the flame.
Carrying out the analysis of the change in the amount of actively released heat in the combustion process from the excess air factor (Figure 8a), one can see that on the regimes where there is an active combustion, the values approximately on one curve. The exception is the depletion zone when working on CNG ($\alpha = 1.26 – 1.37$) where there is a sluggish burning, which affects the reduction of heat dissipation efficiency.

The dependence of the amplitude of the ion current of the electrical conductivity of the flame front on the composition of the mixture is shown in Figure 8b. Where it can be seen that, for the ionisation probe 2 remote from the spark plug, all the points lie on one curve, regardless of the amount of hydrogen added. For the ionization sensor 1 located near the spark plug, the amplitude of the signal when operating on the CNG is slightly lower than the corresponding values with the addition of hydrogen.

![Figure 8](image_url)

**Figure 8** – Dependence on the coefficient of excess air at varying the proportion of hydrogen: (a) the amount of actively released heat in the combustion process; (b) the amplitude of the ion current of the electrical conductivity of the flame front

Estimating the possibility of monitoring the progress of the combustion process by ionization sensors, an analysis of the electrical conductivity. The following regularities are revealed, which relate them to the heat release parameters. On the Figure 9 shows the dependencies of the amount of actively evolved heat at the moment the signal appears on the sensor from the amplitude of the ion current signal when the fraction of hydrogen.

For the ionization sensor 1, some decrease in the amount of released heat from the moment of ignition until the appearance of a signal on the ionization sensor. This is due to the fact that the combustion process, which develops more actively, quickly forms a stable flame front and begins to spread through the combustion chamber. For this reason, a stratification is observed between the values in Figure 9a when working on CNG and CNG with hydrogen additives. Considering the second ionization sensor, we note the presence of a characteristic dependence. Which shows that for large amplitudes of the ion current signal, an increase in the amount of released energy is characteristic at the time of the appearance of the signal at the ionization sensor. This is due to the fact that the increase in the amplitude of the ion current signal is associated with high combustion rates. Consequently, at the time the signal appears on the sensor, the volume of the fresh mixture is less. The absence of a clear correlation between the amount of released energy at the moment of the appearance of the ion current on the first sensor is explained by the close arrangement of the electrode to the spark plug (distance between them 7 mm) and the high stochastic ignition and combustion process. The obtained data show that for evaluation of heat release in the cylinder of the engine, the sensor located in the more remote part of the combustion chamber is more informative. Since it summarizes the effect of hydrogen on the combustion process in the first and second phases.
The estimating the relationship of finer parameters of electrical conductivity to the rate of heat release, the notion of "current density" on the sensor, that is this is the average value of the signal. Also, the average rate of heat generation in the signal zone at the ionization sensor is shown, indicating the average amount of released heat on the 0.27 degree steps of the rotation angle. The dependence of these parameters is shown in Figure 10, where Figure 10a is the dependence for the first ionization sensor, and Figure 10b for the second ionization sensor.

**Figure 10** – The dependence of the specific heat released during the time of the ion current signal on the average voltage density of this signal: (a) on the ionization sensor 1; (b) on the ionization sensor 2

It can be seen from the graphs that the increase in the average value of the ion current signal reflects the increase in the average rate of heat release in the zone of the ionization sensor. The principal effect of the change in the share of hydrogen in gas fuel on the increase in the average specific heat release rate in the ion current detection zone on the first ionization sensor was not detected. At the same time, for the second ionization sensor, there is a difference between the given dependence when working on CNG and CNG with hydrogen additives.

It is more correct to evaluate the characteristics of the entire flame conduction signal for the intensity of chemical oxidation reactions in the flame front, but for engine control systems, the parameter of the...
amplitude of the ion current signal. Therefore, the dependence of the magnitude of the amplitude of the ion current signal on the average voltage density of this signal was shown, as shown in Figure 11.

![Figure 11 – The dependence of the amplitude of the ion current signal on the average voltage density of this signal](image)

The dependencies for the ionization sensor 1 in the spark plug and ionisation probe 2 observed in Figure 11 have a similar picture, and in rough approximation they can be put on one straight line. Thus, the most easily determined and easily correlated parameter of the electrical conductivity of the flame remains the amplitude of the ion current signal. As a result, the most informative is the sensor remote from the spark plug, where the flame front has already formed and the signal has an easily readable shape.

4. Conclusion

1. The presented results of experimental studies show a significant effect of hydrogen on the rate of heat release. And also, as the analysis of the electrical conductivity shows, the effect on the rate of chemical oxidation reactions in the flame front, which is reflected by an increase in the amplitude of the signal and an increase in its uniformity.

2. The possibility of determining the parameters of the heat release rate from the electrical conductivity. As the specific, that is, from the start of the combustion process to the appearance of the ion current, and locally, in the detection zone of the flame signal at the sensor electrode. It is shown that the stability of the signal removed from the spark plug of the ionization sensor is higher and it is easier to interpret it in the characteristics of the heat release rate.

3. The possibility of estimating the efficiency of the combustion process by signals from ionization sensors is shown, which makes it possible not only to estimate the fuel surplus, the composition of the gas fuel, but also the rate of heat release and, consequently, the efficiency of the combustion process, which shows the wide possibilities for regulating the working process.

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