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ESTIMATING AIR-FUEL MIXTURE COMPOSITION IN THE FUEL INJECTION CONTROL PROCESS IN AN SI ENGINE USING IONIZATION SIGNAL IN THE COMBUSTION CHAMBER

SZACOWANIE SKŁADU MIESZANKI W PROCESIE STEROWANIA WTRYSKIEM BENZYNY W SILNIKU ZI Z WYKORZYSTANIEM SYGNAŁU JONIZACJI W KOMORZE SPALANIA*

The paper offers a comparison between signals produced by a lambda sensor and ionization sensor to estimate air-fuel mixture composition in the fuel injection control process in an SI engine. The method of measurement is described and characteristics of the ionization signal in the conducted experimental tests are given. The paper also presents a numerical model of the internal combustion engine that was designed and then used in the simulations to examine the usefulness of ionization signal for estimating air-fuel mixture composition. The conducted tests demonstrated the advantage of the controller using the ionization measurement in the combustion chamber over the controller using signals produced by a classic lambda sensor.

Keywords: internal combustion engine, composition of air-fuel mixture, ionization current, fuel injection, spark plug .

W artykule zawarto porównanie sygnałów z sondy lambda oraz czujnika jonizacji do szacowania składu mieszanki w procesie sterowania wtryskiem benzyny w silniku o zapłonie iskrowym. Opisano sposób pomiaru i charakterystykę sygnału jonizacji w przeprowadzonych badaniach doświadczalnych. Przedstawiono stworzony model matematyczny silnika spalinowego, którego użyto do przeprowadzenia badań symulacyjnych, testujących użyteczność sygnału jonizacji do szacowania składu mieszanki paliwowo-powietrznej. Wykazano przewagę regulatora wykorzystującego pomiar jonizacji w komorze spalania w porównaniu z regulatorem korzystającym z sygnału klasycznej sondy lambda.

Słowa kluczowe: silnik spalinowy, skład mieszanki, prąd jonizacji, wtrysk benzyny, świeca zapłonowa.

1. Introduction

There are three control functions which play a vital role in the operation of an internal combustion spark ignition engine: fuel injection control, ignition control and throttle control. Out of the three control functions, the fuel injection control affects the performance of the engine most. Any change in injection parameters affects not only fuel consumption and vehicle power; above all, it determines exhaust gas composition. Fuel injection control requires predicting air fuel mixture composition in the cylinder after the charge exchange [23].

It is very difficult to measure the mixture composition in the cylinder. The most widely used method is to measure it in an indirect manner, using in-cylinder signals which occur in the combustion process. On the other hand, the methods based on cylinder pressure measurement or optical emission from the combustion chamber are impractical to be employed in engine operation [23].

Modern vehicles are equipped with a sensor of air-fuel mixture composition in the exhaust gas, mounted in the exhaust system. The sensor facilitates estimating mixture composition based on oxygen concentration in the exhaust gas. The mixture composition sensor signal is characterized by a long time delay relative to the fuel injection signal. The delay can have values of even dozens of consecutive fuel injections. In the case of an incorrect value of a fuel injection dose, the correction will occur with a considerable time shift. The state with incorrect values of oxygen concentration in the exhaust gas has a clearly negative effect on engine operation, as it decreases combustion efficiency and catalysis of toxic exhaust gas components

(decreased life of an exhaust gas catalytic reactor) as well as leads to the worsening of vehicle ecological properties [3].

In order to minimize the error which occurs when adjusting air-fuel mixture composition, the excess air factor should be much earlier evaluated in a thorough way. An alternative method for estimating mixture composition, with a much shorter time delay is to measure gas ionization in the cylinder of an internal combustion engine. The measurement is done using the cylinder spark plug electrodes as a sensor [20, 24, 25].

The method based on measuring gas ionization current in the engine cylinder has been repeatedly employed to detect knocking [2, 16, 18] and misfiring [17], to determine temperature [13], to estimate cylinder pressure [15, 19, 21] or, finally, to estimate air-fuel mixture composition, proving a strong dependence of ionization signal on mixture composition [1, 22]. Modern methods of analysis for measuring signals SI engines are also based on artificial neural network models [4], which are broadly used in many fields of science [11, 12].

A significant disadvantage of the indirect measurement of mixture composition based on ionization in the cylinder is a considerable dispersion of such signal and local character of the sensor position, i.e. the spark plug located in the combustion chamber. Based on ionization signal in the cylinder, ignition can be controlled [6], yet the available literature offers little information on the suitability of this signal for fuel injection control. The aim of the present paper is to demonstrate the suitability of using ionization signal for fuel injection control owing to a much faster way of measuring mixture composition in the cylinder and better dynamics of the signal produced by the air-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie www.ein.org.pl

fuel mixture composition sensor and its high correlation in the range λ between 0.9 and 1.1.

2. Fuel injection control

Fuel injection control is generally based on oxygen measurement in the exhaust gas by means of a lambda sensor. The sensor of combustible mixture in the exhaust gas has a serious disadvantage of time delay between a change in the mixture composition after injection and the sensor reaction to it, and the value of the time delay depends on whether the mixture changes from rich to lean (or the other way round) and on the sensor temperature [3].

Figure 1 illustrates the fuel injection control registered by the author for a production, four-cylinder car engine. In the experiments, an electronic controller allowing for injection time control was used. Figure 1 shows a reaction of the adjusting correction k_s to the changing, enforced by the author, characteristic of the injection model, expressed as the correction coefficient k . Figure 1a illustrates time intervals for the mixture that is too rich or too lean, occurring right after the disturbance of the injection model characteristic. The control delay is predominantly due to inertia of the air fuel mixture composition sensor. A similar process is shown in Figure 1b, where the rapid and quick change of the model coefficient k by 15 % led the system to adjust to the correct value only after nine seconds, which shows a long rich mixture time burn of the engine.

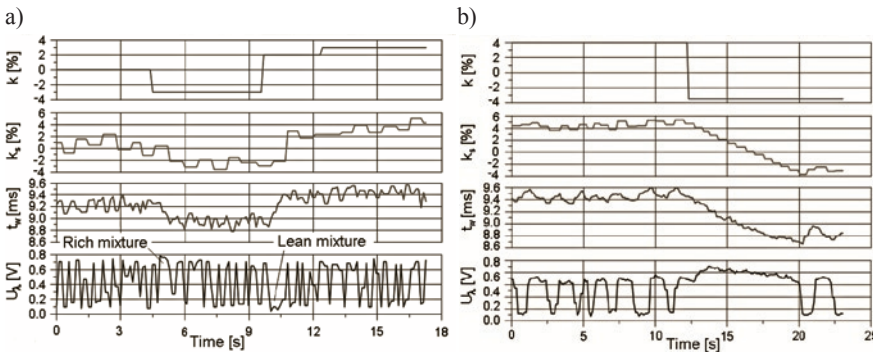


Fig. 1. Fuel injection control in a production, four-cylinder car engine during irregularly forced changes to controller injection model expressed as coefficient k (the author's own research)

3. Ionization signal in the combustion chamber of an internal combustion SI engine

Combustion in an SI engine is initiated by a spark breakdown on spark plug electrodes. The flame propagates along the spark plug and toward the combustion chamber walls, burning the air fuel mixture. Chemical reactions and a temperature increase inside the flame front led to the ionization of charged particles over the whole cylinder volume. The amount of the ionized charged particles is small, yet it can be measured. Following the voltage loss on the spark plug electrodes – i.e. the ionization sensor – a current is induced from free electric

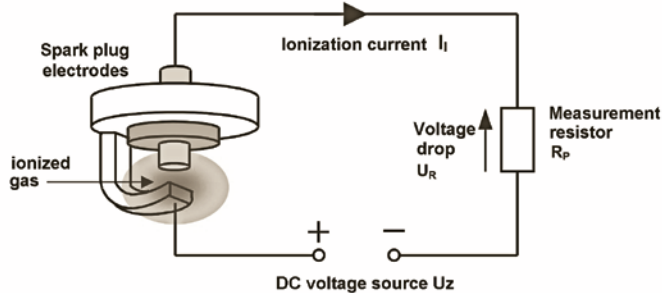


Fig. 2. Method for measuring ionization current between spark plug electrodes



Fig. 3. Measuring system used to measure ionization current in four cylinders

charges contained in the ions. This kind of current is referred to as ionization current.

3.1. Method of measurement

Figure 2 illustrates a circuit for measuring the ionization current. The system is powered by an external DC voltage U_z of 200 V [10]. The current I_i , which flows in the circuit, depends on the conductivity of a gas mixture between the spark plug electrodes in the combustion chamber, i.e. on the value of the ionized gases. The measurement is done on a measurement resistor, R_p , on which the voltage drop U_R (according to the Ohm's law) is proportional to the ionization current.

Figure 3 shows the author-designed measuring system that allows for measuring the ionization current simultaneously in four cylinders of the internal combustion engine.

3.2. Characteristic of the ionization signal in the experimental tests

The experimental tests were performed on a C20LE Holden gasoline engine with a multi-point fuel injection into the inlet manifold, adapted to LPG supply. The C20LE Holden is a four-stroke, four-cylinder, liquid cooled engine, with two valves per each cylinder moved by a single camshaft mounted in the head, equipped with a hydraulic valve adjustment. The engine has a direct ignition system DIS and is equipped with a mechanically controlled exhaust gas recirculation (EGR) valve.

In the experimental tests, a DTS-700 control system for an internal combustion SI engine, co-designed and constructed by the author at the Faculty of Mechanical Engineering at Lublin University of Technology. The apparatus is equipped with four communication interfaces RS232/422/485 and with CAN 2.0B that allow for supervisory computer control of the engine.

The experiments involved measuring the signal of the ionization current in the cylinder, at different values of the excess air coefficient, for set values of the air fuel mixture composition. In the experiments, the following were measured: the pressure signal for the fourth cylinder, the ionization current signal, and two signals describing the

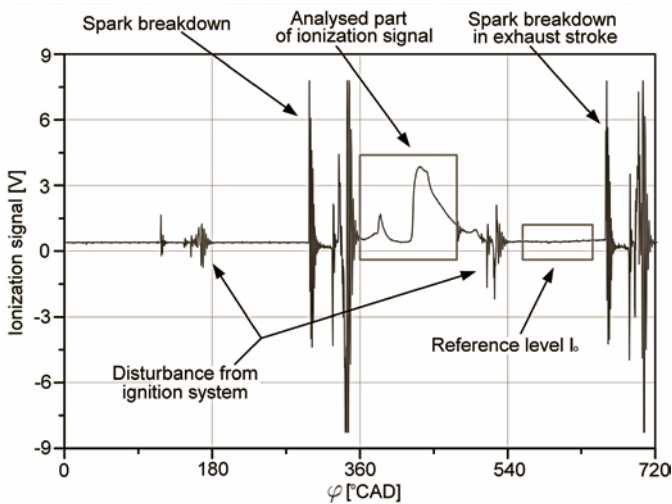


Fig. 4. Ionization signal measured in the fourth cylinder

mixture composition – one generated by the wideband lambda sensor and the other generated by the narrowband lambda sensor. Simultaneously, the TDC indicator signal was being measured.

The cylinder pressure was measured for two reasons:

- to detect potential cases of incorrect combustion (knocking, misfiring),
- to compare dispersions of the pressure signal and ionization signal in the consecutive engine cycles.

Figure 4 shows one of the registered ionization signal waveforms in the fourth cylinder. The following can be distinguished: spark breakdowns, ionization current signal, reference level as well as disturbances from the ignition system.

In order to obtain the required mixture composition, a wideband lambda sensor was used. The assumed mixture composition value was obtained by controlling the fuel injection time. The throttle position can analogically be altered, yet this process is much slower.

The ionization signal has three phases (Fig. 5) [5, 7, 14]:

- a) the ignition phase which lasts until discharge of a coil,
- b) the flame-front phase which covers the period of flame kernel formation until the flame front leaves the area of the spark plug – chemi-ionization is dominant in this phase,
- c) the post-flame phase which covers the remaining time of combustion inside the cylinder – thermal-ionization is dominant in this phase.

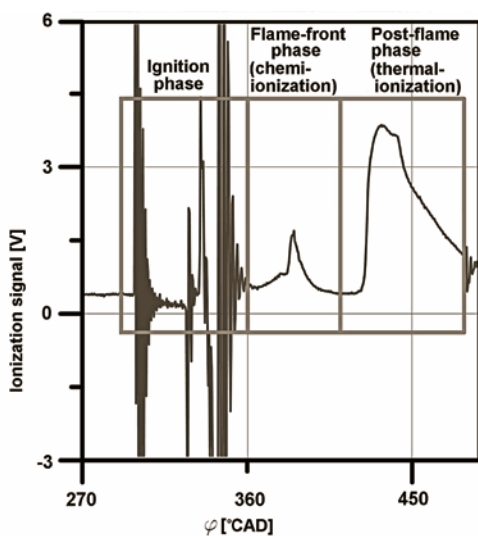


Fig. 5. Fragment of ionization signal characteristic with marked phases

When analyzing the ionization signal, the ignition phase is omitted due to the considerable effect of phenomena generated by the ignition system.

Based on the analysis of the available literature [5, 6, 7, 13, 14, 19, 20, 21] and test results obtained by the author in [8, 9, 10], it was decided that in further analysis a verifiable parameter, I_2 , would be used to describe ionization in the engine cylinder. This constitutes the mean value of the thermal ionization signal.

A model of the parameter I_2 was developed as a second degree polynomial (Fig. 6):

$$I_2 = -12,37 \cdot \lambda^2 + 20,29 \cdot \lambda - 7,09 \quad (1)$$

The correlation coefficient had a value of 0.995, while the quantile of correlation significance t was of 38.78, with only a 2.8 % share of the random component. Next, the rests were analyzed, which proved the normal distribution of the standard error δI_2 , at a test probability of 0.227. The stationarity test allowed for obtaining a quantile of the t-Student test t which had a value of 0.146, i.e. much smaller than the limit value ($t_{\alpha=0,05} = 1.782$). Also, the value of the t-Student test quantile obtained in the symmetry test of the random component was smaller than the limit value ($t = 0.146$), which confirmed the correctness of the model. The correctness of the model was only undermined by the randomness test of the random component, which resulted from a small number of data on which the model identification was based. With the other test results taken into consideration, the developed model can be considered as correct.

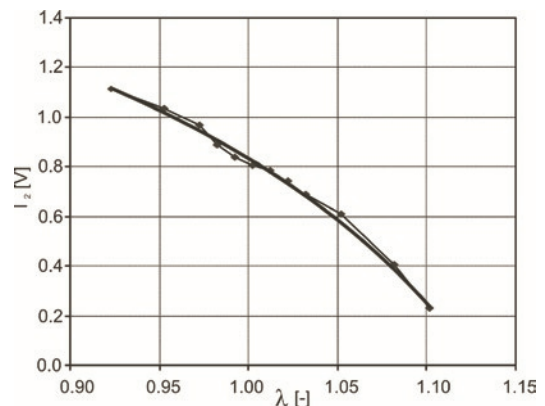


Fig. 6. Characteristics of parameter I_2 in function of λ

3.3. Comparison between the reactions of the oxygen sensor signal to lean burn and enrichment of air-fuel mixture composition

In order to compare the oxygen sensor reaction to lean burn and enrichment of the air-fuel mixture composition, some tests were conducted that involved determining time delay between fuel injection and feedback signals. The obtained results were then used to compare the delays in operation of the lambda sensor and ionization sensor.

The tests were performed at 1000 rpm rotational speed and 40 kPa mean pressure in the inlet system. The engine was in a steady thermal state. The temperatures of both the cooling agent and lubricating oil were maintained at the nominal level. At this stage, the tests consisted in decreasing or increasing the excess air coefficient by changing the injector opening time in an irregular manner.

Figure 7.a illustrates the excess air coefficient set by the fuel injection and the reaction of the classic oxygen sensor to the lean burn. Analogical data are presented in Figure 7.b. The difference between them lies in changing the mixture composition, from lean to rich. The determined time delay of the oxygen sensor signal was specified as

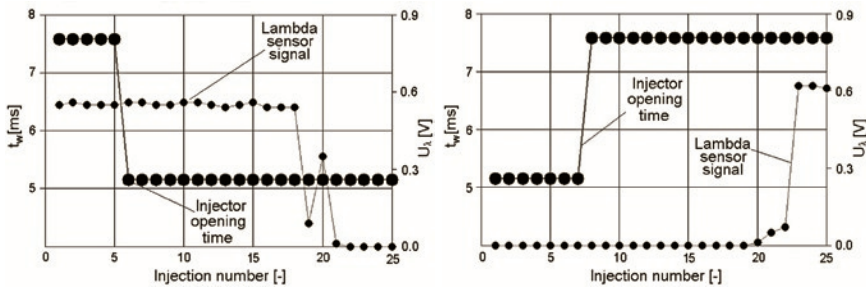


Fig. 7. Fuel injection timing and reaction of classic oxygen sensor to a) lean burning; b) enriching of air-fuel mixture composition

16 consecutive engine strokes (i.e. 16 consecutive fuel injections in a four-stroke, four-cylinder engine).

3.4. Estimating the mixture composition based on signals produced by the oxygen and ionization sensors

Having determined the time delay of the signal from the oxygen sensor relative to changes in the fuel injection time, a PI controller was designed, with the coefficient of mixture composition A_2 set to 0.1. The developed control algorithm was put into the DTS-700 electronic controller.

Figure 8 illustrates the timing for the excess air factor in the course of fuel injection control by the PI controller algorithm based on the lambda sensor signal. Two signals are compared: one estimated on the basis of the fuel injection and the other based on ionization and lambda sensor measurements.

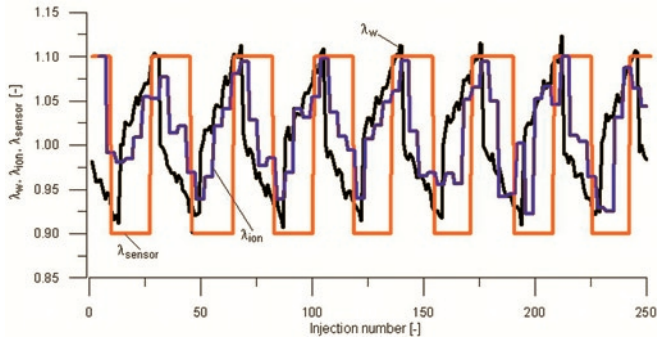


Fig. 8. Timing of excess air factor λ estimated on the basis of fuel injection λ_w , ionization signal λ_{ion} and lambda sensor signal λ_{sensor}

The value of the excess air factor generated during the fuel injection was calculated from the dependence:

$$\lambda_w = \frac{\bar{t}_w}{t_w} \tag{2}$$

where t_w denotes a consecutive value of fuel injection time, while \bar{t}_w denotes the mean value calculated on the basis of all values registered in the experiment (assuming control error symmetry).

The value of excess air coefficient estimated on the basis of the registered ionization signal I_2 was calculated in accordance with a converse model of the dependence (1).

$$\lambda = -0,11 \cdot I_2^2 - 0,05 \cdot I_2 + 1,12 \tag{3}$$

With regard to the lambda sensor signal, it was assumed that the voltage values of the oxygen sensor greater than 0.4 V would de-

note a rich mixture ($\lambda_{sensor} = 0.9$), while the values smaller than or equal to 0.4 V would denote a lean mixture ($\lambda_{sensor} = 1.1$). It should be stressed that the estimation of λ_{ion} was done four times more rarely compared to the signals λ_{sensor} and λ_w , which resulted from measuring the ionization current in only one cylinder of this four-cylinder engine.

The timings given in Figure 8 show that substituting the lambda sensor signal with an on-off control system by the ionization signal with an one-to-one characteristic and a slight nonlinearity and considerably wide range allows for a more accurate estimation of excess air factor values.

It should be stressed that the positive verification of using ionization signal to predict mixture composition will be even more positive after considering (measuring) ionization in all the engine cylinders.

4. Simulations of fuel injection control based on signals produced by the oxygen sensor and ionization sensor

In the simulations, the designed numerical model of a gasoline engine equipped with a control system as well as the results of the simulations conducted with this engine model were used.

The fundamental role of the model was to calculate control as injector opening time based on the injection time under steady conditions and the adjusting correction calculated in the PI controller. The data for calculating the injection time under steady conditions pertained to the assumed cylinder filling, ambient conditions and the adopted value of injector output. The PI controller coefficients were calculated based on the adopted deviation for the mixture composition and time delay of measuring the feedback signal. In the model, ionization signal also based on the signal noise model is simulated.

In the simulations, 10000-cycle fuel injections were calculated, for two types of estimating air-fuel mixture composition and for several variants of the PI controller coefficients.

4.1. Numerical model of the engine with the control system

When designing the model, the following assumptions were made:

- the simulations would involve operation of a four-cylinder engine with 2000 cm³ displacement;
- the cylinder would have 50% filling;
- the injector would be characterized by linear injection.

Given the number of calculations performed, only the final formulae have been presented [10].

The fuel mass injected into the engine:

$$m_{pal} = t_w(i) \cdot w_B \cdot \frac{1}{1 + \frac{k(i)}{100}} \tag{4}$$

where:

- m_{pal} – is the fuel mass,
- t_w – is the injection time,
- w_B – is the injector output constant set to 3.0 [mg/ms],
- $k(i)$ – is the coefficient of variation of the injection model [%].

The real excess air factor:

$$\lambda_w(i) = \frac{m_{pow}}{L_t \cdot m_{pal}(i)} \tag{5}$$

where:

- λ_w – is the calculated lambda value,
- m_{pow} – is the air mass,
- L_t – is the theoretical demand for combustion air set to 14.7 [kg air/ kg fuel].

The control coefficient $k_s(i)$:

$$k_s(i) = \frac{\Delta t_w(i) \cdot 100}{t_w^M} \quad (6)$$

where:

- $k_s(i)$ – denotes the injection control coefficient,
- t_w^M – denotes the basic injection time.

4.2. Simulation results

The simulations were performed for two measurement (estimation) variants of the excess air factor and the following eight values of the parameter A_λ : {0.005; 0.010; 0.015; 0.018; 0.020; 0.025; 0.030; 0.040}. In this way, a synthesis of the PI controller for both variants of mixture composition measurement was conducted.

The timings of the set variation coefficient of injection k_i , the controller response k_s , the fuel injection time t_w , and the air-fuel mixture composition λ directly after the injection are shown in Figures 9 and 10.

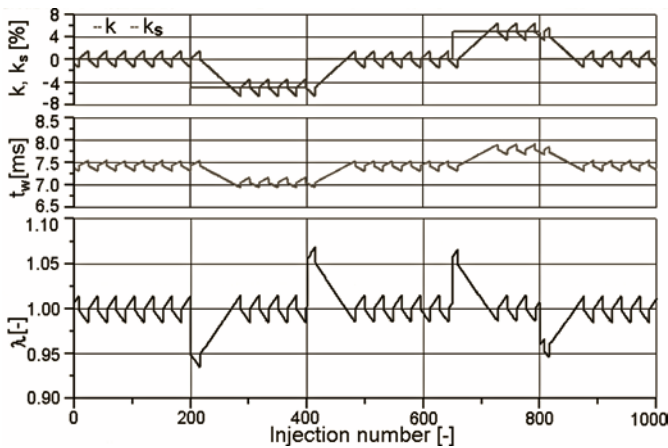


Fig. 9. Injection control with mixture composition measured by oxygen sensor at $A_\lambda = 0.015$

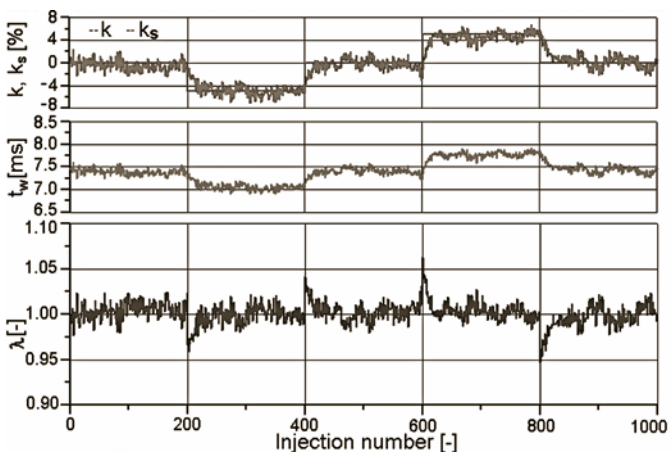


Fig. 10. Injection control with mixture composition measured by ionization sensor at $A_\lambda = 0.015$

4.3. Result analysis

For both variants, three stabilization coefficients of mixture composition were calculated. The following definitions of stabilization coefficients were taken:

1) $\delta_{\lambda 1}$ denotes the coefficient of control error energy $\varepsilon(i)$:

$$\varepsilon(i) = \lambda_w(i) - 1 \quad (7)$$

$$\delta_{\lambda 1} = 1000 \cdot \sum_{i=1}^{10000} \varepsilon^2(i) \quad (8)$$

2) $\delta_{\lambda 2}$ denotes the coefficient of maximum control error:

$$\delta_{\lambda 2} = \int_{i=i_1}^{i=i_2} |\varepsilon(i)|, \quad i \in \{i_1, i_2\}, \quad \text{sign}[\varepsilon(i)] = \text{sign}[\varepsilon(i-1)] \quad (9)$$

$$i_{\max} \in \{i_1, i_2\}$$

where i_{\max} is the maximum error coefficient $\varepsilon(i)$.

3) $\delta_{\lambda 3}$ denotes the mean error coefficient, defined as:

$$\delta_{\lambda 3} = \frac{\delta}{J_{\max}} \quad (10)$$

where:

$$\delta = \sum_{j=1}^{j_{\max}} \sum_{i=i_1(j)}^{i=i_2(j)} |\varepsilon(i)| \quad (11)$$

$$i \in \{i_1(j), i_2(j)\}, \quad \text{sign}[\varepsilon(i)] = \text{sign}[\varepsilon(i-1)]$$

Figure 11 offers a comparison of the dependence of the stabilization coefficients $\delta_{\lambda 1}$, $\delta_{\lambda 2}$ and $\delta_{\lambda 3}$ on the coefficient A_λ . In each presented case, the advantage of the controller using the ionization signal to estimate the mixture composition can be observed.

The optimum values of the PI controllers are located in the vicinity of A_λ equal to 2%, which is consistent with the observations made for real gasoline engines.

The performed simulations demonstrated the advantage of the controller using the measurement of ionization in the cylinder over the controller using the signal from the classic lambda sensor.

5. Conclusions

1. The conducted experimental tests have confirmed the suitability of using an ionization transducer in the combustion chamber to estimate values of mixture composition in the fuel injection control system.
2. A considerable dependence of the I_2 parameter characterizing the ionization signal on the λ coefficient (of the air-fuel mixture composition) was proved. The linear correlation in the range λ between 0.9 and 1.1 exceeded 0.99.
3. It was observed that the time distance between the ionization signal and fuel injection was equal to three power strokes of a four-cylinder, four-stroke engine with injection to the inlet manifold.
4. It was observed that the time distance between the signal from the oxygen sensor and fuel injection was equal up to dozens of power strokes of the four-cylinder, four-stroke engine with injection to the inlet manifold.

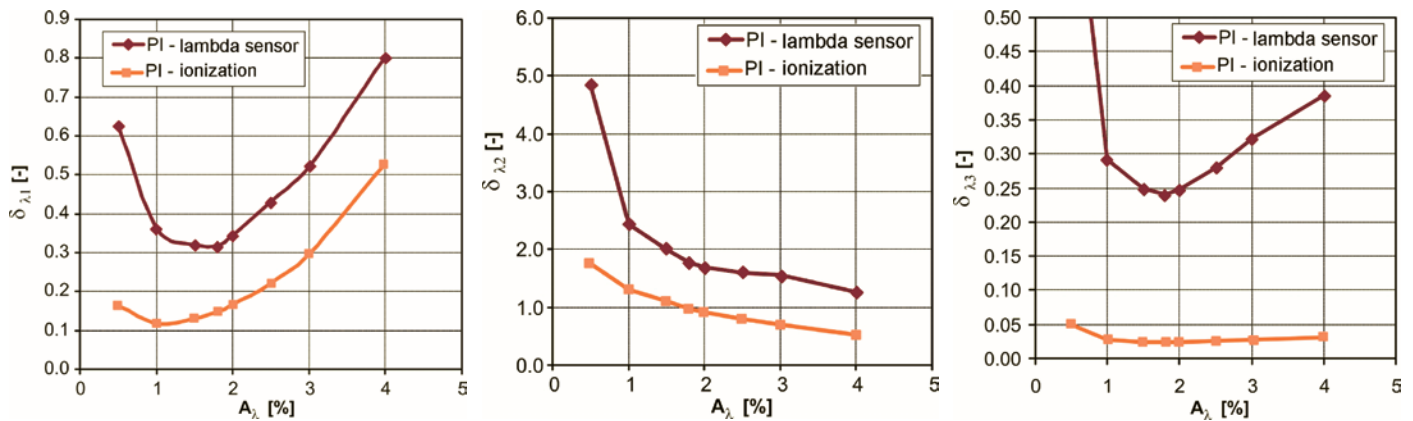


Fig. 11. Dependence of stabilization coefficients $\delta_{\lambda,1}$, $\delta_{\lambda,2}$, $\delta_{\lambda,3}$ on coefficient A_{λ} for both control variants

- By adding to the car engine control algorithm a spark plug ionization signal, an individual control of the mixture composition coefficient in each cylinder will be possible.

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Nomenclature

A_λ	–	assumed amplitude of variation of excess air factor,
I_{jon}	–	ionization current,
I_0	–	reference current for ionization signal,
I_2	–	thermal ionization signal value,
I_I	–	ionization current in measuring circuit,
$k(i)$	–	coefficient of variation of injection model [%],
$k_s(i)$	–	injection control coefficient [%],
L_t	–	theoretical combustion air demand,
m_{pal}	–	fuel mass,
m_{pow}	–	air mass,
$^{\circ}\text{CAD}$	–	crankshaft angle degrees,
R_p	–	resistance of measurement resistor,
t_w^M	–	basic injection time,
t_w	–	injection time [ms],
U_R	–	voltage drop on measurement resistor,
U_z	–	DC voltage in ionization current measuring circuit [V],
U_{jon}	–	voltage of measuring ion density in combustion chamber,
U_λ	–	lambda signal voltage [V],
w_B	–	injector output constant,
ΔI_2	–	thermal-ionization signal deviation,
Δt_w	–	injection time correction,
δ_λ	–	quality control coefficient,
λ	–	oxygen content in exhaust gases,
λ_{jon}	–	calculated value of lambda based on ionization,
λ_{sonda}	–	lambda sensor signal,
λ_w	–	calculated value of lambda.

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