Article citation info:
WIĘCŁAWSKI K, MĄCZAK J, SZCZUROWSKI K. Electric current as a source of information about control parameters of indirect injection fuel injector. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2020; 22 (3): 449–454, http://dx.doi.org/10.17531/ein.2020.3.7.

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ELECTRIC CURRENT AS A SOURCE OF INFORMATION ABOUT CONTROL PARAMETERS OF INDIRECT INJECTION FUEL INJECTOR

PRZEBIEG PRĄDOWY JAKO ŹRÓDŁO INFORMACJI O PARAMETRACH STEROWANIA WTRYSKIWACZEM PALIWOWYM WTRYSKU POŚREDNIEGO*

The article discusses results of the laboratory experiments in which fuel injectors used in indirect injection internal combustion engines were tested. During the experiments, numerous dosing cycles of the injectors were performed while changing the control parameters, due to which, the dosing characteristics were developed and influence of applied parameters on the resultant fuel flow determined. Simultaneously, the voltage and electric current waveforms in the injector coil were recorded, due to which finding links between the electric current characteristics and the determinants of the injector work was possible. The investigation has shown that parameters of electric current constitute a precise criterion for assessing the operation of the solenoid valve, because fuel flow is created due to the work ofelectric current. Thus, by observing the changes in the current flowing through the valve coil,it is possible to monitor precisely the correctness of the process of opening the flow and the electric current intensity, at which the flow began and to determine the mechanical quantities such as fuel dose and pressure. As a result, a characteristic is developed, that provides the links between the fuel pressure and the electric current at the point of lifting the needle, which is quite a novel approach. Such a characteristic can be used in diagnostics and control of fuel injectors as well as all kinds of electromagnetic valves.

Keywords: *injector, injector diagnostics, indirect injection, current waveform.*

Artykuł przedstawia wyniki eksperymentów laboratoryjnych polegających na testowaniu wtryskiwaczy paliwowych stosowanych w silnikach spalinowych z wtryskiem pośrednim. Podczas eksperymentów wykonano wiele cykli dawkowania wtryskiwaczy zmieniając parametry sterowania, dzięki czemu opracowano charakterystyki dawkowania i określono wpływ stosowanych parametrów sterowania na wynikowy przepływ paliwa. Jednocześnie rejestrowano przebiegi napięcia i natężenia prądu elektrycznego w cewce wtryskiwacza, dzięki czemu możliwe było powiązanie charakterystyk prądowych z determinantami pracy wtryskiwacza. Wykazano, iż parametry prądowe są precyzyjnym kryterium oceny pracy zaworu elektromagnetycznego, ponieważ dzięki wykonanej przez prąd pracy powstaje przepływ paliwa. Zatem poprzez obserwację zmian prądu płynącego przez cewkę zaworu, można precyzyjnie monitorować prawidłowość procesu otwierania przepływu oraz natężenie prądu, przy którym przepływ się rozpoczął oraz określać wielkości mechaniczne jak dawka i ciśnienie paliwa. Wynikiem badań jest opracowanie charakterystyki wiążącej ciśnienie paliwa z natężeniem prądu w punkcie podnoszenia iglicy, co jest podejściem nowatorskim. Taka charakterystyka może być wykorzystana w diagnostyce i sterowaniu wtryskiwaczy paliwowych oraz wszelkiego rodzaju zaworów elektromagnetycznych.

Słowa kluczowe: *wtryskiwacz, diagnostyka wtryskiwacza, wtrysk pośredni, przebieg prądowy.*

1. Introduction

The paper discusses results of the laboratory experiments, the purpose of which was finding links between the electric current parameters, controlling the work of the electromagnetic injector, and its mechanical parameters. Using the relation of mechanical parameters and the electric current quantities allows for supervision of the injector work and precise evaluation of the quality of individual injection phases, i.e. to control the technical condition of the fuel system and the injector during operation, all on the basis of the easily-observed current parameters.The knowledge of the relationship between these parameters can be applied not only in injector diagnostics but also to control injectors. This results from the fact that thanks to the work of the electric current, the fuel flow supplied to the injector under sufficient pressureis induced. The electric current flowing through the valve coil, generates the magnetic flux, and subsequently, the magnetic force acting on the needle (the element cutting the fuel off). This force, after overcoming all resistant forces, preventing this action enables lifting the needle. Additionally, the electric connection of the injector coil provides for both, its control and power supply. To summarise, the work of the magnetic force resulting from the flow of the electric current is a factor allowing for connecting the current with the mechanical quantities. Due to the accurate defining of all the above relations, the real starting and finishing points of successive phases of the fuel injection process can be determined, which, in turn, can be used in managing the engine work. Such identification may allow for developing a different strategy relative to the control logic commonly applied so far.An engine controller can be developed using continuously updated information about the real beginning andduration of individual injection phases. Such a controller will adequately correct the control of injectors, in case there were variations detected in starting and finishing of the dosing process, contrary to the methods used nowadays, that are based solely onmeasurements of the exhaust gases quality and corrections of injection parameters on the basis of the previously pro-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** grammed maps [1]. The size of a fuel dose, determined on the basis of the current waveform integration, can serve as an additional verification of the control process,within a given control method of the flow of electric current through the injector coil.The profound knowledge of momentary parameters of injection phases may be used for precise injector diagnostics, too, therefore contributing to the early detection of failures that could affect the degradation of the exhaust gases purification system and even the engine damage. Thus, the early detection of damages in the fuel system is particularly vital.

Operation of a fuel injector may be evaluated on the basis of various quantities. Verified can be the control signal or the control result, i.e. the quality of the generated stream [3]. Shape, angle, and degree of the mixture atomization proves the quality of the dose obtained. Lee et al. [5], conducted an analysis of the dynamic behaviour of the solenoid valve while examining the phenomenon of electromagnetic field and flow through the exhaust channel [10]. In her work, Harantova [2]discussed a projectand analysis of the control and supply systems for injectors.Voltage of the injector power supply and pressure values in the fuel system at a given width of the control pulse (PWM - Pulse-Width Modulation)were analysed [9].At the same time, attempts were made, to achieve the highest possible efficiency and stability of the injector work. In [12], the method of fuel injector verification based on electric current characteristics and the possibility of correcting the operation of the injector by using appropriate control algorithms was presented. Tan et al. [14] shows how to adjust the injector control strategy to take into account changes in the resistance and inductance of its coil, taking into account the effects of aging. Nikolićet al. [8] discussed the processes occurring in the fuel supply systems, namely fuel injection, generation of the fuel mixture, combustion, and exhaust emissions. K function, as a correlation between the speed of the fuel flow and fuel pressure depending on its type [4] [11] was determined. Fluctuations in the fuel pressure have a major impact on the atomization, combustion and size of the fuel stream, as well as on delays in the injector operation [6] [7]. Stępień [13] described the process of sludge formation in the injector fuel channels, the impact of the resulting sludge on changes in diagnostic parameters indicating the degree of degradation of the injector. In [4], a novel method was discussed, using Coriolis flowmeters (CFM), and a new, patented technique of signal processing for measuring the fuel flow. Measuring the flow speed of individual injectors of the engine in real time was proved possible, which enables the accurate assessment of the injection process. Merola et al. [7] presented a method of verifying fuel injection and the combustion process using optical diagnostics, using an endoscopic system coupled with a CCD camera mounted in the intake manifold.

The abovementioned works are examples of current publications regarding methods of evaluation of the fuel injector operation. It is a final element of the fuel system and undisturbed engine work depends highly on its flawless functioning. Defects of the injector may lead to degradation of the exhaust purification systems (catalytic converter). This is why the appropriate diagnostics and control of the fuel injector is a particularly important operation-related issue. In the following sections, an innovative diagnostic method forfuel injectors and all kinds of electromagnetic valvesis discussed. This method is based on identification of values of the intensity of electric current controlling the injectorat the point of lifting the needle. The value of the current at this point is not a constant. It is dependent upon several factors resulting fromthe injector's properties and control parameters. Accuracy of determination of the values of the electric current and the detailed analysis of the determinants for injector control allows forusing the correlation between the value of the electric current at the characteristic points of the current-related waveform of the dosing injector and its mechanical parameters. On the basis of observation of the characteristic current-related points, practically all electric and mechanical failures of the injector can be detected, with no need of OBD-based diagnostics or other methods, including those based on removing the injector from the vehicle engine. The method of diagnostics presented in this article may be applied during operation without removing the injector from the engine, and after appropriate implementation in the engine controller, an automatic tool is obtained, that will ensure an early detection of damage in both, the injector and the fuel system. In the subject literature regarding the diagnostics of fuel injectors, there are no methods mentioned, that are based on the correlation described in Section 3 of this article.

2. Dose and fuel flux

The electric current parameters precisely describe the phenomena they affect. This is illustrated in Fig. 1, where the increasing surface area under the current waveform (continuous red line) reflects the ever-increasing flow of the specific mediumin response to the prolonged voltage impulse from 2 ms to 15 ms. In each of the waveforms in fig. 1, at 0.6 V there is a dotted dark blue line, denoting the photodetector reading, transforming the laser light into the voltage. In the tests performed at the test bench, the stream of fuel disturbed the laser light running under the injector nozzle (decreased voltage output by approx. 0.15 V), illustrating the real fuelflow.

The injector work is based on an undisturbed cooperation of the electric and hydraulic systems, controlling of which is supervised by the electronic system. The current flow during the preset injection time is defined by the continuity equation:

$$\nabla j + \frac{\partial \rho}{\partial t} = 0 \tag{1}$$

where: j – electric current density,

$\nabla j = \frac{\partial j}{\partial x} + \frac{\partial j}{\partial y} + \frac{\partial j}{\partial z}$ – scalar multiplication with the nabla vector operator,

ρ – density of electric charge,

t – time [s].

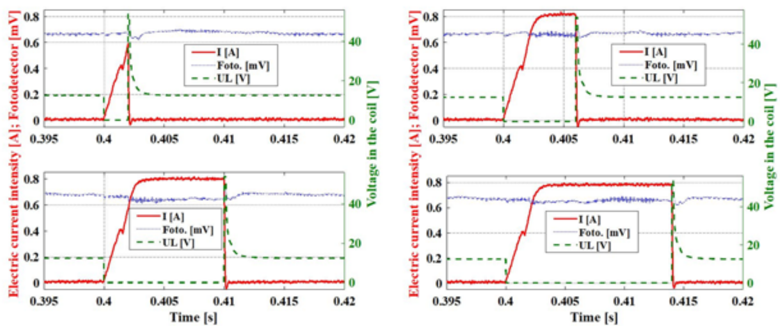

Fig. 1 Waveforms of fluctuations of electric current, voltage, and intensity of laser light corresponding to the increased injection times, from 2 ms to 15 msregistered at the test bench

The electric current density$j$is a result of differentiation of the electric current relative to the surface where it flows:

$$j = \frac{dI}{dA} \tag{2}$$

where: I – electric current [A], A – cross sectional area [m^2].

The motion of the injector needle results from the change in the magnetic flux φ, which in turn is a result of the electric current I flowing through the coil. This is described as a flow of the electric charge Q:

$$Q = \int_{t_1}^{t_2} i(t)\,dt = \frac{1}{RQ}\int_0^{\varphi} \frac{d\varphi}{dt}\,dt = \frac{\varphi}{R} \qquad (3)$$

where: R isresistance [Ω]and φ -magnetic flux [Wb].

Due to the flow of electric charges, the fuel flow is obtained, described by analogical equation. The stream continuity equation:

$$\rho * \nabla v + \frac{\partial \rho}{\partial t} = 0 \qquad (4)$$

In this formula, v denotes volume $\left[m^3\right]$.

Changes in flowing fuel flux may be correlated with the electric charge flowing during injector's dosing action. Using the current-related waveforms allowed for generating the characteristics of the dose and of the fuel flux, mapping the electric current waveforms. For instance, at the injection time of $10\,ms$ and the injection pressure $p = 0.3\,\text{MPa}$, the obtained stream flux amounted to: $0.0061 \pm 0.000124 \frac{\text{mg}}{\text{ms}}$, which is related to the flow of the electric charge $Q = 0.00668\,\text{C}$. The electric charge Q was computed by integrating the current-based waveform (3). Subsequently, the theoretical volume of the fuel stream was calculated in accordance with the equation (5):

$$\dot{m} = f_{s-c} * A * \rho * \sqrt{\frac{2*(p_1 - p_2)}{\rho_i}} \qquad (5)$$

where: f_{s-c} – flow coefficient,

ρ_i – density of fuel during flow through the injector nozzle,

p_1 – pressure of fuel before the injector,

p_2 – pressure of fuel after the injector.

In the example shown above $(10\,\text{ms and } 0.3\,\text{MPa})$, the obtained mass flow amounted to: $0.00556 \frac{\text{mg}}{\text{ms}}$. The result is burdened with a measurement error resulting from the uncertainty of parameter measurements from equation (5) such as: fuel pressure or fuel density. The result of the calculation differs from the actual by $0.000416 \frac{\text{mg}}{\text{ms}}$. Because of the uncertainty of the measurement of the quantity from equation (5), it is a satisfactory result.

Fig. 2 showscurrent waveforms for different voltage pulse widths, from 1.6 ms to 10 ms, superimposed on each other.

An electric charge $q_{1,6ms} = 0.000418\,\text{C}$ has been assigned to the 1.6 ms range (first range from the left in Fig. 2, indicted by a golden continuous line), while range of 10 ms (the whole of the current waveform – marked with the red continuous line) has an electric charge of the value $q_{10ms} = 0.00668\,\text{C}$. The difference between $q_{1,6ms}$ and q_{10ms} is 16–fold. The areas of successive ranges as well as electric charges are proportional to their corresponding values.

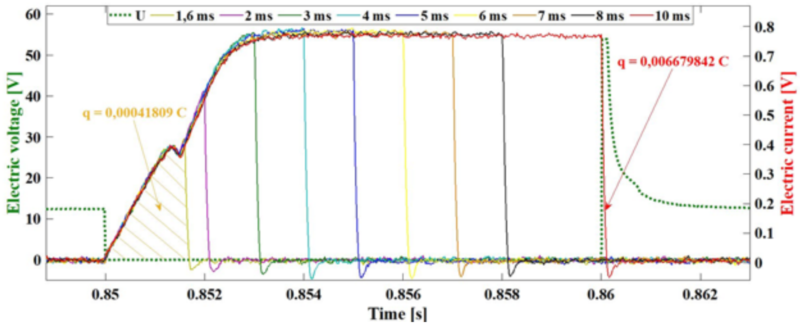

Fig. 2. Current waveforms for different voltage pulse widths, from 1.6 ms to 10 ms, superimposed on each other, with the assignment of the area under the waveform

In the case of the current ranges for various fuel pressure values (Fig. 3), the differences between electric charges representing successive current waveforms are too small to assess (on the abovementioned basis) at which value of the fuel pressure the dose was generated and what its size was. These values lie within therange of measurement uncertainty. The size of the dose and stream can be related to the value of the fuel pressure, defined on the basis of electric current value at the point of the needle lifting, which will be the main focus of the second part of this article.

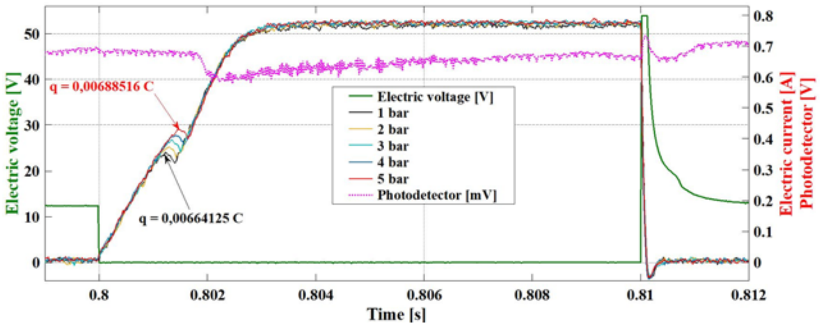

Fig. 3. Current waveforms for increasing values of fuel pressure, from 0.1 to 0.5 MPa

3. Fuel pressure

The current waveform recorded during generation of a single fuel dose, with a preset eight-millisecond length of a control pulse is shown in Fig. 4. The electric circuit of the injector coil consists of the source of the electromotive force (ε_0), resistance (R), and inductance (L) (circuit RL). Increase in the current in the RL circuit is described by the Kirchhoff's equation (6), defining the shape and values of the electric current varying over time. In the case of the injector's current waveform, as a result of the work by the magnetic force, i.e. lifting of the needle, equations describing the electric current must take into consideration the resistance overcome by this force, which is discussed in this section of the article.

$$I_{op} = \frac{\varepsilon_0}{R} * \left(1 - e^{\frac{R}{L}}\right) \qquad (6)$$

The shape of the waveforms observed during the work of the electromagnetic valve depends not only on the electric current parameters (current intensity, voltage) and geometry of the valve core. Location of the characteristic points (both value and the time lapse) depends on the specific density of the flowing medium and value of the pressure that reaches the valve.In this part of the article reference is made to bench tests in which the pressure downstream of the injector was constant. Therefore, the results refer only to the pressure before the injector. The purpose of the analysis is to show the trend of changes in electric current at the needle lifting point depending on the pressure (in fact, the pressure difference before and after the injector). During the engine operation of the injector, the pressure in the intake manifold changes, which change must be taken into account in the analyzes performed.

The fuel flow into the injector inlet channel totally changes the time-related voltage-current waveform. As a result of the fuel density and pressure action (it is density, in fact, since pressure causes its increase), a greater magnetic force needs to be generated in order to lift the needle. At the specific value of current at the point where the needle is lifted (I_{op}), a corresponding pressure value of the fuel before it reaches the valve needle, can be precisely matched $\left(p_{inj}\right)$. Fig. 4 shows two injector current-related waveforms, for two different fuel pressure values before the injector. Change in the injection pressure from 0.2 MPa to 0.8 MPa results in a change in the current at the point where the needle is lifted, from 0.379 A to 0.495 A.

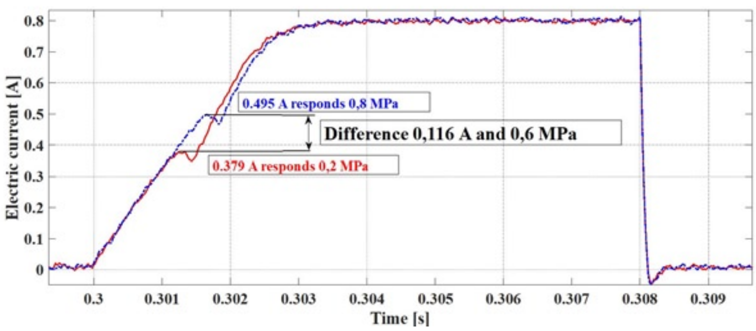

Fig. 4. Graphic representation of the relationship I_{op} (p_{inj})

On the basis of the laboratory research, for each injector type, the function of relationship of the current intensity (at the point where the needle is lifted) and the injection pressure can be determined:

$$I_{op} = f\left(p_{inj}\right) \tag{7}$$

The fuel flow can be obtained after the magnetic force F_m has overcome all the forces counteracting the needle lifting:

F_p – force resulting from the fuel pressure,

F_i – inertial force,

F_f – frictional force,

F_s – force of the spring.

$$F_m > F_p + F_i + F_f + F_s \tag{8}$$

Magnetic force F_m is a derivative of the energy originating in the coil as a result of the current. The magnetic force sufficient to lift the needle is defined by means of the current intensity, measured at this point of the current-related waveform of the injector I_{op}. The most significant resistant force is force F_p, the remaining elements are constant or vary based on this force's change. The consequence of it being that the magnetic force F_m is a function of the current intensity I_{op}. And the current intensity I_{op} is a function of the force resulting from the fuel pressure p_{inj}:

$$F_m = f\left(I_{op}\right) \tag{9}$$

where: F_m – magnetic force resulting from the magnetic flux [N],
I_{op} – current intensity at the point of the needle lifting [A],
p_{inj} – fuel injection pressure [MPa].

For the increasing fuel pressure, the force necessary to lift the needle grows, thus the current required to generate the magnetic flux of the adequate value, increases, too:

$$I_{op1} = f\left(p_1\right) < I_{op9} = f\left(p_9\right)\left\{p_1 < p_9\right\} \tag{10}$$

Relationships (10) are graphically represented in Fig.5. It shows an image of the current waveform of injector with the increase in current intensity at the point of the needle lifting marked, depending on the injection pressure.

Current intensity at the point of needle lifting, (Fig.5) corresponds closely to the injection pressure. Moreover, it is unrelated to the injection time, it depends on the value of generated magnetic force. The greater the difference between the pressure before the injector and the pressure in the intake manifold (after the injector), the higher the current I_{op}. The mapping of such a characteristic in the relation (6) required using the coefficient f_{press}. After inserting the coefficient into the differential equation, in the component $\frac{\varepsilon_0}{R}$ (6), the expected value of the current I_{op} will be obtained (11):

$$I_{op} = \left(f_{press} * \frac{\varepsilon_0}{R}\right) * \left(1 - e^{\frac{R}{L}}\right) \tag{11}$$

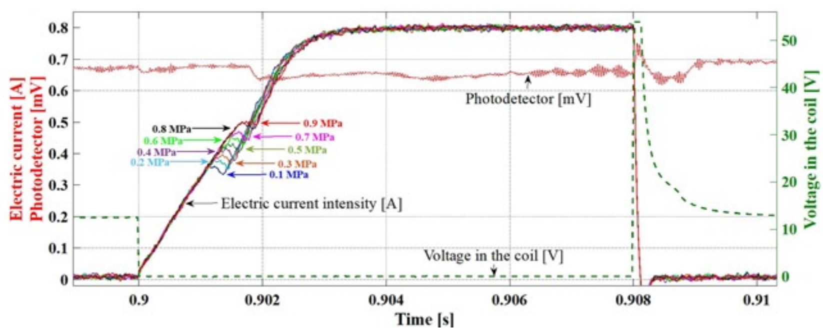

Fig. 5. Changes in electric current intensity at the point of the injector needle lifting at different injection pressure values

The first component determines the maximal value that will be reached I_{op}, whereas the second component affects the exponential tending to this value (Kirchhoff's equation). Due to the expression (11), the resistant forces in the current-defining equation in the circuit of the working injector (circuit RL) are taken into consideration, which can be observed in the equations modelling the current ranges in the previous section. Characteristic I_{op} (p_{inj}), necessary in the detailed modelling of the injector current waveform can be utilised to evaluate the given injector's technical state, in comparison to different types of injectors or in the early diagnosing of its faults. All kinds of defects of the electromagnetic valve will result in change in the current intensity at the point of the needle lifting. The injector can be monitored during its work, controlling this parameter and the value of injection pressure from the pressure sensor. Characteristic $I_{op}\ (\ p_{inj})$ is a relationship of the linear character. As the pressure keeps growing, a little increase in the proportion of the current intensity I_{op} to p_{inj} can be observed. Characteristics $I_{op}\left(p_{inj}\right)$ have been developed for several different types of injectors with different degree of wear. For a given type of injector, characteristics have similar character but they are not identical, which results from the differences in their operation. The characteristic of the injectors "a" and "b" (Fig.6) changes throughout the whole range of the injection pressure (from 0.1 to 0.8 MPa).

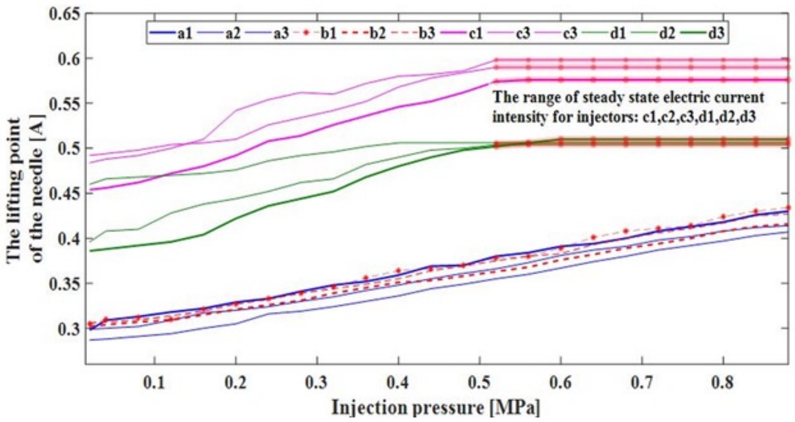

Fig. 6. Characteristics $\boldsymbol{I_{op}} = \boldsymbol{f}\left(\boldsymbol{p_{inj}}\right)$ *for injectors: "a", "b", "c" and "d"*

The magnetic flux resulting from the flowing current, generated around the coils of these injectors is greater than the generated by the coils of the injectors "c" and "d" (Fig.6). The current intensity for injectors "c" and "d" from pressure of 0.5 MPa transitions into the steady state (maximal – horizontal line). Above this pressure value, they do not increase their doses and the current intensity at the point of the needle lifting is constant (such as the current intensity of the steady state in the circuit). Ability to overcome the forces counteracting the needle lifting at the lower current I_{op} indicates a given injector's greater efficiency.

The characteristic of the relationship between the electric current at the point of the needle lifting and the mechanical resistances of the lifting action results from the electrical and geometric propertiesof the injector, fuel system, and preset control parameters. A precise determination of the corresponding parameters allows for verification of the technical state of the fuel system, also in the real time. This innovative approach may be applied both in diagnostics and to introduce corrections in injector control. The presented analysis shows that on the basis of the selected points of the time-related current-voltage waveform, observed during injector dosing, such parameters of injector control as the injection pressure can be determined, and combining this information with the surface area below the current intensity waveform, allows for characterising the mass flow.

4. Summary

The article discusses results of the laboratory experiments testing fuel injectors used in internal combustion engines with the indirect injectionwithout turbo boost. In the course of experiments, waveforms of voltage and current in the injector coil were recorded. Also, the dosage characteristics were developed; the influence of applied control parameterson the resultant fuel flow was determined. On the basis of the above, it was indicated that the current-related parameters constitute a precise criterion for the injector work evaluation. Correlation of the current waveforms with dosage parameters of the fuel injectors enabled the conclusion that fluctuations within the waveforms result not only from the current-related properties. They also depend on mechanical properties affecting the flow (4), such as density, injection pressure, or resistance of the needle motion. The conclusion can be made that the shape of the waveform of the electric current (6)in the circuit of the injector coilcontains information about mechanical parameters of injection (11), as well as electric and mechanical properties of the injector. The range of the current waveform or the flowing electric charge (3) can be correlated with the fuel flux(5). In order to map the fuel dose precisely, it is necessary to determine at what pressure value occurred the fuel flow. The characteristic point of the current waveform, used in the discussed analysis. The value of the current at this point relates directly to the forces counteracting the lifting action (8). The largest of these is the force resulting from the fuel pressure, which is one of the variables. The second variable is the pressure downstream of the injector, i.e. the pressure in the intake manifold. The reference to the current at the needle lifting point makes sense under the same comparison conditions, i.e. with current pressure control downstream of the injector.

A conclusion can be made that a radical change in the electric current at this point takes place following the change in the fuel pressure (7), which has been proved by the performed laboratory experiments.

Observation of the electric current waveforms and analysis thereof, in combination with the previously generated characteristic of correlated parameters, allows for verification of the correctness of the fuel dosing process, and for rendition of the assessment of technical state of the fuel system and the injector. The presented current waveforms may be monitored by means of the controller in the real time, during operation, due to which such verification can support the OBD and the control systems for the exhaust emissions, allowing for a faster failure detection in the fuel system. The relation between the value of the electric current at the point of needle lifting and the fuel pressure may be used not only in fuel injector diagnostics but also to verify different kinds of electromagnetic valves.

The results of laboratory experiments presented in this work reflect a new viewpoint regarding the fuel injector diagnostics. An additional diagnostics discussed here may be used in the real time during operation of the injector or electromagnetic valve. The „on-line" diagnostics can contribute to an earlier detection of damages, thus protecting the exhaust purification system from degradation and even from engine damage. The function of the fuel pressure can be also used to control the injectors. Determination of the real injection phase may help managing the engine work. This means the change of strategy relative to the one used so far. The presented information could be applied in the module controlling engine work, using in the control algorithm the information on the real moment of starting and finishing the process of dosing, and not be functioning only on the basis of the previously developed algorithms, corrected through the adaptation of control and the lambda probe.

Acknowledgement

Project financed by the National Centre for Research and Development under the DOB-BIO9-04-02-2018 programme.

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