Control of fuel through the injector, based on the observation of the electric current waveform

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Abstract. The article discusses results of the laboratory experiment investigating the gas injector of the dual fuel engine supplied with diesel fuel and propane-butane mixture, mapping the real conditions of the injector operation. During generation of fuel doses, the current waveforms on the injector coil were registered. A detailed analysis of the variations of the function representing the current intensity and voltage, allows for determination of the lifting and closing points of the injector’s needle with the microsecond accuracy, based on the phenomenon of changes in injector core inductance during the needle movement. This enables optimization of the injector control. The coefficient of the fuel flow through the injector needle \( f_{c-s} \) has been developed, to be used in computations of the theoretical flow through the needle. Due to the above, the exponential increase in the fuel flow through the nozzle has been modelled, resulting from the exponential rise in the current pulse, performing the work of lifting the injector needle. The presented model is based on the analysis of the current waveforms. The authors do not analyse the mechanical forces counteracting the needle opening because change in the current and voltage at the injector coil defines precisely the actual position of the needle, and it determines the mass of the flowing fuel. On the basis of the presented paper, injector control (control of the solenoid valve) can be optimised and the losses resulting from the time shift in the injection pulse can be reduced.

1. Introduction

This article discusses results of the laboratory experiment, in which a gas injector of the dual fuel engine supplied with diesel oil and propane-butane mixture was tested. During the experiment, real conditions of the injector operation were recreated. The laboratory test bench was built using the vehicle assemblies. Due to automation of the experimental process, a great amount of measuring data was collected, used later to analyse the gas flow in the injector and most of all to determine the real opening and closing times of the injector needle. There exist many publications describing the flow through the injector. The tests were conducted at the laboratory test benches, determining the flow with the mass flow meter [1,2,3]. Mathematical models [4] were employed in analysis, using simulation programmes such as Matlab Simulink. Delays in opening and closing the gas injector have been discussed, based on the measurement of the increase in the pressure wave downstream of the injector, generated after its bias control [5]. The analysis discussed in this paper has been performed on the basis of the current-voltage waveforms as referred to the injector coil.
2. Laboratory stand for testing the gas flow through the injector

In order to perform the analysis of the gas injector work, a laboratory stand was built, allowing for injection of the gas doses similar to the actual doses. The test bench (Fig.1), was described in detail in previous publications [6]. The tests conducted at the stand were carried out again. The difference lies in the automation of measurement, an automatic recording of parameters and the possibility of the ongoing display of the preset parameters and those received from sensors, including information acquired from the WLC2 scales, as well as in expanding the data with the current and voltage records of the injector control.

![Figure 1. Laboratory appliances during testing](image1)

![Figure 2. Control panel in LabVIEW environment](image2)

3. Laboratory stand for testing the gas flow through the injector

The tests consisted in generating gas doses with pressure compensation. Pressure compensation was achieved by controlling the injection pressure so that it was always greater by one bar than the downstream pressure (in a dose container). The injection (duration) times range from 1.5 ms to 9 ms, whereas the range of injection pressure – from 2.0 to 2.7 bars. Series of several hundred injections were carried out, then the obtained sums of doses were divided by the number of injections, and so the single mass dose for a given injection time and pressure was obtained. After programming the parameters of the investigative cycle, the measurement was conducted automatically. The difference between the tests previously carried out at the test bench and the current tests was the fact that the $U_{c}$ controller voltage, the $U_{inj}$ injector voltage, and the intensity of the current supplying the injector $I_c$ were measured.

Sampling of the acquired data related to the measured current values amounted to 51.2 kHz. Due to the automation of the data acquisition process, and the automatic generation of plots within the LabVIEW environment (Fig.2), a wide range of results for all the individual injections was obtained, which is a huge statistical database where every individual injection is described with a set of parameters. Transformation of the results into the Matlab programme facilitated analysis of the obtained measurements.

4. Experiment results. LPG dose and mass flow

Figure 3 shows gas doses in relation to pressure in the gas tank (downstream). On the y axis, gas doses in milligrams are shown, on the x axis – the LPG injection time (duration). With controlling the dose with pressure compensation upstream and downstream of the injector, the increase in the dose is obtained, together with the increase in pressure, which results from the rise in the gas density. The mass of the gas flowing through the nozzle is determined by the dependence:
\[ m = \alpha \cdot \bar{Z} \cdot A \cdot \sqrt{2 \cdot \frac{\Delta p}{\rho}} \cdot \Delta \theta \]  

where:
- \( \alpha \) - flow coefficient
- \( \bar{Z} \) - expansion ratio
- \( A \) - surface area of the nozzle [m²]
- \( \rho \) – specific density [kg/m³]
- \( \Delta p \) – differential pressure before and after the injector [Pa]

\[ \sqrt{2 \cdot \frac{\Delta p}{\rho}} = \dot{w} \] [m/s], velocity of fuel movement, the first derivative of displacement, hence the designation, mass flow - \( m \)

**Figure 3.** LPG doses in relation to the injection pressure, at different injection times (duration)

Gas flow through the injector is illustrated in Figure 4. On the y axis the gas flow in milligrams per millisecond is shown, on the x axis - the injection pressure. The gas flow above the injection time 2.6 ms, is included in the magnitudes not significantly differing from each other (range of the tenth of mg/ms).

**Figure 4.** Flowing gas stream

It results from the fact that the magnitude of the gas stream is influenced by the injector opening and closing times. Influence of these quantities on the gas stream is more visible at the small injection times.
This is why the formula of the gas mass flow should be supplemented with the flow coefficient, dependent on the injector opening and closing times, in accordance with the following proportion:

$$f_{c-s} = \left(2 - \exp\left(\frac{t_{op}}{t_{inj}+t_{cl}}\right)\right)$$  \hspace{1cm} (2)

where:
- $t_{inj}$ - LPG injection preset time
- $t_{cl}$ - injector closing time
- $t_{op}$ - injector opening delay time

The next steps to develop the coefficient given below. The given values ($t_{inj}$, $t_{cl}$, $t_{op}$), are parameters available during the laboratory experiment. The numerator provided to increase the size of the dose, in the denominator – decreasing:

$$\frac{t_{inj} \times t_{cl}}{t_{op}}$$  \hspace{1cm} (3)

Obtaining a growing coefficient, it requires changing the numerator with the denominator:

$$\frac{t_{op}}{t_{inj} \times t_{cl}}$$  \hspace{1cm} (4)

Figure 5. Distribution of maximum flows

The maximum flow in the figure 5 have an exponential distribution, which follows from the equation (8). Exponential nature of accruing electric current, translates into an exponential distribution of growing fuel streams. For this reason, the quotient (4) in the exponent of the Euler number was placed:

$$\exp\left(\frac{t_{op}}{t_{inj} \times t_{cl}}\right)$$  \hspace{1cm} (5)

To obtain the distribution of the coefficient from zero to one, the equation (5) from the number 2 was subtracted:

$$f_{c-s} = 2 - \exp\left(\frac{t_{op}}{t_{inj} \times t_{cl}}\right) \{0 \div 0.99\}$$  \hspace{1cm} (6)

then:

$$A(f_{c-s}) = \begin{cases} 0 & f_{c-s} = 0 \\ A & f_{c-s} = 1 \end{cases}$$  \hspace{1cm} (7)
Figure 6, shows the distribution of values which takes the quotient (6) and the flow coefficient. The purpose of the $f_{c-s}$ coefficient is mapping the real flow through the injector nozzle and the nonlinear dose increase at the growing injection time $t_{inj}$ (8):

$$m = 3 \times \left(2 - \exp\left(\frac{t_{op}}{t_{inj} \times t_{cl}}\right)\right) \times A \times w \times \rho$$  \hspace{1cm} (8)

![Figure 6. Distribution of values of the flow coefficient](image)

5. Current waveforms

Injector opening time depends on:
- injection pressure – pressure “before” the injector,
- pressure in the tank, into which the dose is injected – pressure “after” the injector,
- density of the agent passing through,
- preset injection time (duration),
- current and voltage supplying the injector coil.

When the injector needle closes the nozzle, pressure upstream of the injector acts against its opening. After an initial partial lifting of the needle, the flow of an agent starts and the force counteracting the further lifting of the needle diminishes. For this reason, the injector opening time $t_{op}$ does not change linearly with the changed injection time, pressure, and gas density. The following factors influence the delay time of the injector needle lifting [5]:

- $F_E$ – electromagnetic force in the injector coil [N],
- $F_S$ – force of the injector spring [N],
- $F_G$ – force generated by the injection pressure [N],
- $F_B$ – inertial force of the injector needle [N],
- $F_T$ – friction force between the needle surfaces and the needle cylinder surface [N].

$$F_E = F_S + F_G + F_B + F_T \ [N]$$  \hspace{1cm} (9)

Electromagnetic force in the injector coil $F_E$ [N]. The analyse of the delays in injector needle travel on the basis of the waveform of the current flowing through the injector coil is possible, instead of considering all the forces from equation (9). Current flowing through the injector coil represents the sum of forces (9), which must be balanced by the current with the generated electrodynamic force. The circuit of the injector coil can be considered as a circuit of electrical resistance $R$, inductance $L$ (with active electromotive force $\varepsilon$) in series. If the inductance of the injector coil would be a constant value, then the Kirchhoff equation would be sufficient to model it:

$$R I + L \frac{dI}{dt} = \varepsilon$$  \hspace{1cm} (10)

After solving this equation and inserting the time constant of the circuit:
\[ \tau = \frac{L}{R} \Rightarrow L = R \cdot \tau \]  

We obtain:

\[ I = \frac{e}{R} (1 - e^{-\frac{t}{\tau}}) \]  

(12)

As a result of the change in the injector inductance, resulting from the change in the position of the needle, we get two transient states with different time constants. First transient state when the needle closes the nozzle of the injector:

\[ \{ dL = R \cdot \tau_0 \} \Rightarrow I_0 = \frac{e}{R} (1 - e^{-\frac{t}{\tau_0}}) \]  

(13)

and a second transition state when the needle is raised.

\[ \{ dL = R \cdot \tau_1 \} \Rightarrow I_1 = \frac{e}{R} (1 - e^{-\frac{t}{\tau_1}}) \]  

(14)

This is presented on Fig. 7. Voltage \( U_L \) of the inductance \( L \) is described by equation (15):

\[ |U_L| = L \frac{dI}{dt} = \varepsilon \cdot e^{-\frac{t}{\tau}} \]  

(15)

6. **Current waveforms – Laboratory experiment**

In the laboratory experiment, waveforms of the injection voltage and the current flowing through the injector coil were recorded for successive injections. Analysis of these parameters allows for determination of the delay time of the injector opening \( t_{od} \) and the closing time of the injector needle \( t_{cl} \). Together with the growing injection time \( t_{inj} \), a growth of the maximal current can be observed as well as the expansion of the current pulse, represented by the red line (Fig. 7). The time of current growth increases after full lifting of the needle \( t_{ko} \) as well as the time of the current steady state \( t_{ss} \). Figure 7 illustrates changes in voltage and intensity of current flowing through the injector coil during generation of a gas dose. The graph was accomplished at the following injection parameters:

- injection time \( t_{inj} \) = 9 ms
- pressure in the container, where the dose was injected \( p_c \) = 1.8 bar
- injection pressure \( p_{inj} \) = 2.8 bar
- supply voltage: \( U_c \) = 12V

According to equation (8), the growth of current (red line) is of an exponential nature. Automation of the 9-millisecond injection begins at \( t = 0.334s \). The current starts increasing to the value of 1.4 A, in the time of 1 ms, in which the electromagnetic force is smaller than the sum of forces making the needle shut (the force of a spring and of the injection pressure \( p_{inj} \)). How fast the current grows depends on, in accordance with equation (12), the time constant of the coil \( \tau \), and the tangent of the angle of a line tangential to the current waveform and the time axis is a value of the current derivative at a given point. From this point on the plot, a slope of the tangential current growth can be observed. It is a point marking the beginning of lifting of the injector needle, \( t = 0.335s \) (needle stroke). The current plot becomes a nearly horizontal line. This state lasts about 400\( \mu \)s. It is the time of travel (stroke) of the injection needle till its complete lifting. The complete lifting of the needle is the point \( t = 0.335375 \) s. From this point on, the exponential current growth takes place, but with the completely lifted injector needle yet, up to the point \( t = 0.3385 \). After achieving the steady state, the current maximal value is maintained \( i = 4.7 \) A, which allows for keeping the needle lifted. To summarise, controlling the injector with the time \( t_{inj} \) = 9 ms, enables obtaining the following time components:

- current growth at the closed injector nozzle \( t_c \): 1000 \( \mu \)s
- needle lifting time \( t_l \): 400 \( \mu \)s
- time from bias control to complete opening $t_c = t_{ic} + t_l$
- exponential current growth to the steady state (nozzle open) $t_{ss}$: 3400 µs
- current steady state $t_{ss}$: 4200 µs
- $t_{cl}$ – actual time of injector closing (after current decay): 2400 µs.

The value of the needle closing time will be explained below. The actual time of the lifted injector needle is $t_{ic} = 10.4$ ms, where a time of a completely lifted needle equals to: 7.6 ms, transient states (needle movement) - 2.8 ms. This explains the non-linearity of the characteristics of the injector doses.

$$t_{ac} = t_i + t_{lo} + t_{ss} + t_{cl} = 0.4ms + 3.4ms + 4.2ms + 2.4ms = 10.4ms \quad (16)$$

For the injection time $t_{inj} = 1.7$ ms:

$$t_{ac} = t_i + t_{lo} + t_{ss} + t_{cl} = 0.2ms + 0.3ms + 0ms + 2.07ms = 2.57ms \quad (17)$$

The complete flow for the injection time $t_{inj} = 1.7$ ms lasts about 0.5 ms. In the closing phase, the flow decreases exponentially to zero.

Figure 7. Waveform of the injection current at $t_{inj} = 9$ ms and $p_c = 1.8$ bar

In this non-steady state, the flow is but partial. This explains, why at such a short injection time the dose is generated at all. Naturally, values of the shown times are approximate but due to the precise measurement cards the presented precision seems satisfactory. Figure 7 shows a spike in the induced high voltage caused by the current switch off, which is marked on the line of the control voltage. The range of the voltage spike exceeded the measuring range of the measurement card, this is why there is a horizontal line in the figure in this place. Determination of the closing time of the injector needle requires referring to the relationships discussed in Chapter 5 and analyses of the obtained voltage characteristics.

Figure 8 illustrates the current-voltage waveform for $t_{inj} = 2.6$ ms and $p_c = 1.8$ bar. The plot in the figure was divided into sections corresponding to the successive states of the needle position. These states were discussed above, up to the moment of switching off the control current. The point of closing the needle, in this case 1760 µs - after switching off the impulse controlling the injector. The above was concluded after analysis of the voltage decay (green line), from the time 0.703 s in Figure 8. According to (15):

$$|U_L| = L \frac{di}{dt} = \varepsilon * e^{-\frac{t}{\tau}} \quad (15)$$

Voltage decreases exponentially after switching off the current, in accordance with the characteristics in Figure 8. Simultaneously with voltage decrease, the coil inductance changes because of moving of the needle towards the nozzle (the needle sliding out of the coil). After stopping the needle at the injector nozzle, inductance stops changing and it remains steady at the constant level. As a result of these changes, a short 100 µs-voltage spike resulting from equation (15) is obtained, after which the voltage decays exponentially to zero, again. At the points of the plot (Fig.8), marked with the green circle, the exponential voltage decay ceases to be smooth, thus determining the point of the flow closure. This change could be noticed due to sampling with the frequency of 51.2 kHz. There exists a very precise measurement of the closing point of the injector needle. The closing time around 1.76 ms, at the injection
time 2.6 ms, appears a long time. It should be remembered though, that due to the nozzle being closed, the flow is only partial. Such a relatively long closing time can be explained by the fact that the needle is closed by means of the spring, and the injection pressure acting towards its closing (until the needle is fully closed), exerts pressure on it, in all directions, which causes partial balancing of these forces. The obtained results require further elaboration. The data should be processed statistically, determining the measurement uncertainty and the deviation range resulting from the possible inaccuracies of measurements.

7. Summary
Observation of the current growth in the injector needle allows for determination of the injector needle travel during its lifting, whereas observation of the voltage decay enables precise determining of the needle closure point. Instead of considering all the forces acting on the needle (9), it is sufficient to analyse the current-voltage waveforms in the course of generating the flow.

The current waveform reflects the sum of all the resistance, which must be balanced by the generated electrodynamic force resulting from the current. The closing point of the injector needle was determined due to the analysis of relationships regarding the RL circuit (10) and the obtained characteristics. The phenomenon of the change in the injector coil inductance caused by the moving injector needle during closing the gas flow proved helpful (Fig.8). The actual time of the injector opening is a sum of: the operation delay, needle lifting, steady state and needle closure delay. Transient periods and their proportion to the steady state decide about the total volume of the gas dose. For the reason of delays in lifting and closing the injector needle, the precise information about the actual needle position and shifting of the flow through the needle in time, is of paramount meaning for control. On the basis of the presented paper, injector control (control of the solenoid valve) can be optimised and the losses resulting from the time shift in the injection pulse can be reduced.

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