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MODIFICATION OF A FOURTH GENERATION LPG INSTALLATION IMPROVING THE POWER SUPPLY TO A SPARK IGNITION ENGINE

MODYFIKACJA INSTALACJI LPG IV GENERACJI POPRAWIAJĄCA JAKOŚĆ PROCESU ZASILANIA SILNIKA O ZAPŁONIE ISKROWYM*

Fourth generation LPG installations are fuel systems which, apart from their obvious advantages, have numerous disadvantages. One of their weaker elements are the injectors, or rather their improper performance. It was therefore justified to undertake a modification of the alternative fuel system in order to improve its work. The modification itself was preceded by a series of bench and road studies. A mathematical model of the injector was developed, which was later used in simulations. The results of the tests enabled the preparation the fuel system modification project involving the introduction of additional injectors and a system that controls their work. The complete unit was installed in a test vehicle and the modification's effect on the fuel supply process is presented in the results of conducted tests.

Keywords: *LPG injectors, injector modelling, LPG installation modification, gas installation diagnostics, injector performance control.*

Instalacje LPG IV generacji są układami paliwowymi, które oprócz oczywistych zalet, mają liczne wady. Jednym ze słabych punktów takiej instalacji są wtryskiwacze, w właściwie ich nieprawidłowa praca. Wobec powyższego podjęto próbę opracowania modyfikacji alternatywnego układu zasilania, usprawniającą jego pracę. Modyfikację poprzedzono szeregiem badań stanowiskowych i drogowych. Opracowano model matematyczny wtryskiwacza, na podstawie którego przeprowadzono badania symulacyjne. Wyniki pozwoliły na wykonanie projektu modyfikacji układu paliwowego. Zmiany polegały na wprowadzeniu dodatkowych wtryskiwaczy oraz układu sterującego ich pracą. Całość zamontowana została w pojeździe testowym, a wpływ wprowadzonej modyfikacji na jakość procesu zasilania pokazują wyniki przeprowadzonych badań.

Słowa kluczowe: *wtryskiwacze LPG, modelowanie wtryskiwaczy, modyfikacja instalacji LPG, badania instalacji gazowej, sterowanie pracą wtryskiwaczy.*

1. Introduction

An LPG installation, similarly to other fuel supply systems, has its advantages and disadvantages. The primary advantages of this fuels system (mainly, the reduction of operation costs) are well-known among drivers. The disadvantages are not so notable among users, although they are equally or even more important.

It has been observed that recently, the intensity of research on fourth generation gas installations has decreased, mainly due to the technological advances in vehicle design (mass introduction of direct fuel injection). Modern combustion engines required the development of new solutions for gas installations, using the fuel in its liquid state (LPLi) [5].

The installation of an alternative fuel system usually entails a decrease in the engines usefulness factors (power and torque). This, however, can be alleviated with a well-designed intake system. The heat necessary to change the state of LPG can be obtained from inlet air, thanks to which the temperature of the fuel increases while the temperature of the air is decreasing, contradictory to its density. The engine's volumetric efficiency is therefore improved [11] and, consequently, it produces more power and torque.

Injection of any type of fuel (LPG included) entails decreasing its pressure (the pressure of LPG before the injector is higher by approximately 1 bar than the pressure in the engine's inlet line [2]). Expanding fuel draws energy in the form of heat from its nearest surroundings (the outlet nozzle and the air drawn by the engine), which in extreme cases may lead to ice forming on the injector nozzle and cut off the supply of LPG. This situation depends on the geometry of the injector (mainly, the diameter of the outlet nozzle) and the engine's operating parameters. The operating parameters of an engine are determined by the users of the vehicle, its designers may however, through optimization for example, change the geometry of the elements of the fuel supply system, and therefore prevent extensive cooling of injector nozzles [6].

A team of scientists in South Korea has indicated that the composition of the fuel-air mixture has a significant influence on the velocity

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** of the flame of the combusted LPG, which in turn has a great impact on the composition of the exhaust gases. Research has shown that the most favourable combustion velocity is observed for a stoichiometric mixtures. The worst results were noted for poor mixtures. Therefore, precision dosage of fuel is essential [7]. Often, in order to obtain a stoichiometric mixture in the full range of engine speeds it is necessary to use an additional controller to supervise the fuel supply in neutral gear, or the engine is controlled using the H-infinity method [4]. In the 1990s, some designs used an additional injector activated at high engine speeds [15].

The appropriate composition of the fuel-air mixture ensures low emission of harmful carbohydrates and carbon oxides. Another significant component of exhaust gases are the nitrogen oxides which are created in consequence with the high temperatures inside the combustion chamber. The use of an exhaust gas recirculation system (EGR) results in a decreased emission of nitrogen oxides. This system is usually controlled by the data encoded in the ECU, which in most cases was devised in-factory for conventional fuel (petrol). The use of alternative fuel systems (such as LPG) entails problems with the proper functioning of the EGR system (the amount of recirculated gasses is too high or too low [3]). Applying an additional, automatically adjustable controller may eliminate this problem. The use of such controller would ensure proper functioning of the exhaust gas recirculation system, even if the conditions in the engine very rapidly [3].

It is also important to dose the fuel uniformly, measured both between particular cylinders as well as between consecutive work cycles of the engine. What is important here is the quality of the LPG injectors, which is often unsatisfactory (considering the criteria used by the manufacturers of combustion engines) [8]. The uniformity of the LPG dosage determines the composition of chemical compounds in the exhaust gasses. The nitrogen oxides content increases in direct proportion, while the amount of carbon oxides and carbohydrates increases in reveres proportion the value differences in the LPG dosages in particular injectors. These differences, in brand new injectors, can be as high as 15% [8].

Numerous analyses of exhaust gasses of combustion engines indicate that LPG fuel systems are more favourable that units fuelled conventionally [12, 14]. Bearing in mind that there is still a vast number of vehicles using fourth generation gas installations (particularly in African countries), the author of this article is convinces that work on improving the design of this fuel system should be continued. The focus here is on the issues with the LPG engine fuel supply, since even the smallest improvement in the engine's performance or fuel consumption may have a significant impact in the global scale.

Preliminary road tests indicated that the gas installation swithes off for some time during acceleration [2]. Similar behaviour was observed in fuel supply systems in other vehicles confirmed the suspicion that this is not an isolated case in special conditions. Preliminary bench tests and numerous consultations helped to determine that one of the reasons for the improper functioning of the fuel supply system are the injectors, or rather their design. However, later experience showed that the injectors are not the only reasons behind the described situation. The situation may also be caused by the reducer, or rather its limited efficiency [9].

The LPG injector is an electric valve that opens and closes the supply of fuel. The design of the gas injector is significantly different from the design of a petrol injector. In its vapour phase, the volume of LPG is higher than the volume of petrol in its liquid state, therefore the overall dimensions of a gas injector are significantly higher. The increase of the dimensions is, however, connected with higher inertial forces of the injector's moving elements [9]. The base components of the studied gas injector are: the needle valve, coil, return spring, sealing-suppressing elements, and a multi-part casing. The main element of the casing (the rail) is also the duct that supplies the fuel to the injector. It also serves as the nest for the needle valve of the injector (Fig. 1).

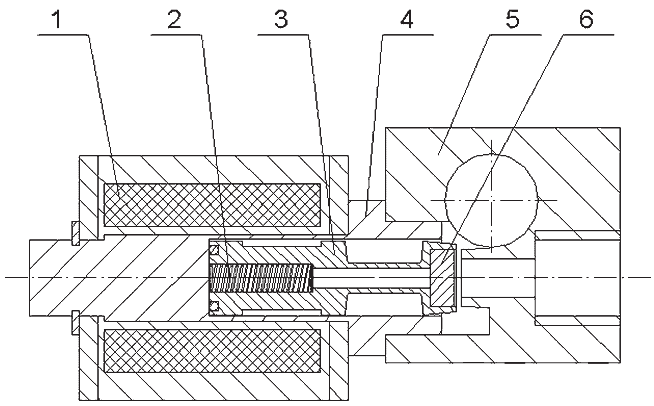

Fig. 1. Fourth generation LPG injector diagram: 1– coil, 2 – return spring, 3 – needle valve, 4 – cylinder, 5 – injector rail, 6 – sealing-suppressing element

The needle valve that moves inside the injector opens or closes the fuel flow. The closing movement is caused by the return spring and the opening movement results from the electromagnetic force generated by the injector's coil. This force is initiated by an electrical impulse from the controlling unit. The LPG controller uses impulses generated by the engine's ECU, dedicated for petrol injectors on the basis obtained from the sensors that monitor the engine's operation (coolant temperature, amount of inlet air, acceleration pedal position, etc.). Based on this data, the gas installation controller selects a proper impulse path from its encoded "map", corrects it against the temperature and the pressure of the LPG, and then sends it to the gas injector.

Most of the LPG injectors manufactured today can be divided into two groups: those of high precision and those of high efficiency. A third group of efficient injectors is a costly alternative, as it is characterised by short interval for both opening and closing.

In the neutral gear and with low fuel supply, it is necessary to measure out precise doses of fuel. The precision of the dosage is significantly influenced by exact measurements of the duration of injection. A precise injector, characterised by low efficiency, must have an appropriately long opening time, in which case the precision of the dosage increases. Problems occur, however, under high stress (with high supply and engine speed) [17]. The low efficiency of the injector results in a too long gas injection period, which exceeds the engine period cycle. The engine is supplied with a poor fuel dosage. Modifying the design of the injector in order to increase its efficiency enables proper dosage under stress, yet it makes the dose imprecise under low stress and in short opening periods.

A properly designed (configured), installed and adjusted gas system, equipped with rapidly opening and closing injectors, guarantees precise composition of the fuel-air mixture in all working conditions. This however entails increased production costs, and consequently increases the price of a gas installation (universal installations are of course less expensive that dedicated installations). It has been observed that for most users, the main criteria of the usefulness of a gas installation are the economical aspects [10]. Therefore, many of such installations are installed and later maintained by incompetent or inexperienced people who charge a low price for their services. An analysis of client behaviour of a car services station showed that approximately 90% of its users service their cars in authorised stations only during the warranty period. After its expiry, the users look for cheaper alternatives.

2. Fuel supply system examination before the modification

The modification of the fuel supply system began with the identification of the problem. As stated in the introduction, the gas installation switches off under certain conditions of work. This occurs when the engine is extensively supplied with fuel (when the duration of the supplying impulse is extended) and the engine speed is high (when the engine cycle is shortened).

In order to confirm these statements, the changes in the controlling signals were measured for both petrol and LPG injectors. The measuring tools consisted in a portable computer and an HD-Scope 9.0 oscilloscope. The voltage on the injectors was measured every 1000 rpm (from 1000 rpm to 5000 rpm). The measurement was based on recording the flow of the signals for approximately 10 seconds, three times for each engine speed. One of the measuring channels of the oscilloscope was connected to the petrol injector's power connector and another measuring channel was connected to the LPG injector's power connector.

The tests were performed on a BMW 520i equipped with a six cylinder M50B25 engine (capacity: 1991 cm^3, power: 110 kW) and an alternative, fourth generation LPG fuel supply (comprised of: a Vector 6 controller, Zavoli Zeta-N reducer, PS-01 pressure sensor, and a Valtek 3Ω injector rail), giving a better look on the conditions of the unfavourable behaviour [2]. At low engine speeds and with small supply, the gas installation works properly. Problems begin to occur with the increase of both the engine sped and the supply level. As shown in Figure 2, at engine speed of approximately 5000 rpm, the voltage on the injector does not drop to zero. The intervals between particular work cycles are short (up to several ms), making it impossible for the injector to close [16]. The engine is therefore supplied constantly. With further increase of the engine speed (up to 6000 rpm, Figure 3), it can be observed that the gas installation switched off (loss of the impulse signal that controls the work of the injectors), while simultaneously starting the conventional, petrol fuel supply (appearance of signals controlling the petrol injectors).

The numerical simulation of the injector needle valve, prepared on the basis of a mathematical model [1], showed that the gas injector begins to not shut properly already at engine speed of 4600 rpm (Fig. 4).

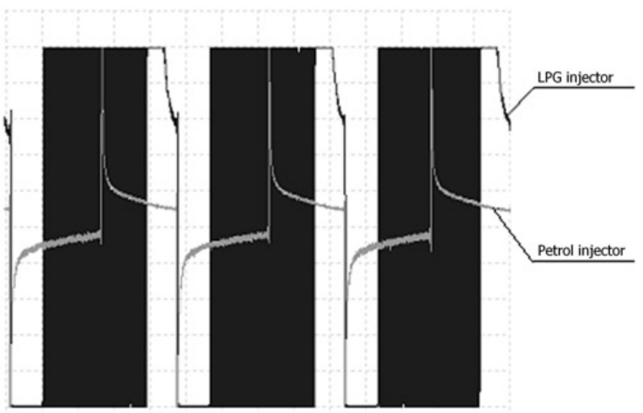

Fig. 2. Voltage changes in the petrol (grey) and LPG (black) injector at maximum engine supply and 5000 rpm engine speed [2]

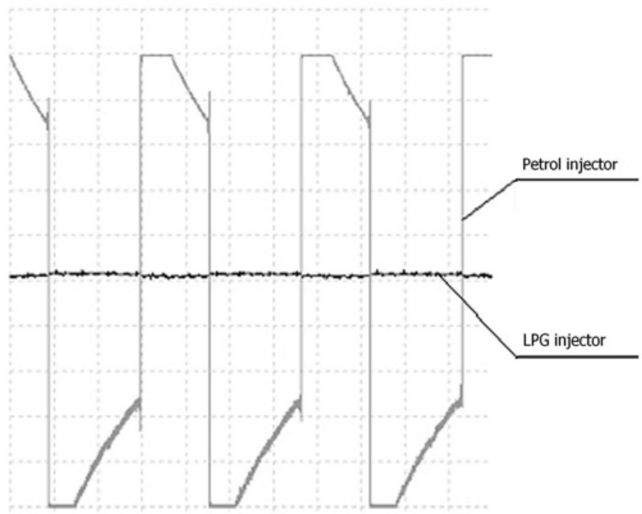

Fig. 3. Voltage changes in the petrol (grey) and LPG (black) injector at maximum engine supply and 6000 rpm engine speed [2]

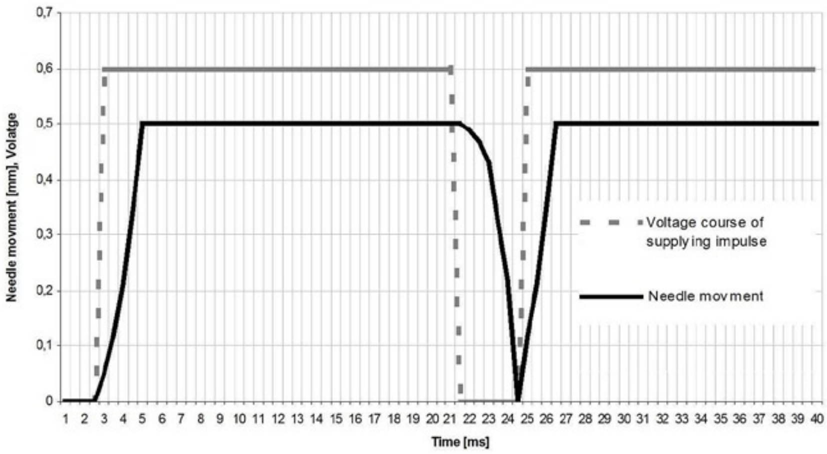

Fig. 4. The simulation of the movement of the needle at engine speed of 4600 rpm

Knowledge of the conditions of the described issue allowed to determine that the occurrence of the disturbance in fuel supply depends strictly on the individual driving style of the driver and, of course, in some cases it may not occur at all.

3. Modification of the fuel supply system

The occurrence of improper closure of injectors has a definite negative influence on the factors used to evaluate the supply system (power and torque, fuel consumption and economic factors). Therefore it was justified to prepare a modification that would allow the engine to be supplied with gas in full range of its work. Among several solution, the final choice was the one that was based on doubling the number of injectors so that each cylinder would ultimately be supplied by two injectors working alternately. The diagram of such supply is presented in Fig. 5.

The proposed solution will cause every injector to open at half of its originally planned frequency (that is, once per every four turns of the crankshaft). The increase of the intervals between work cycles should allow the needle valve to shut freely and cut off the supply of fuel, and it should also allow the supply larger doses of LPG than now. Therefore, after implementing the changes in the design, the alternative fuel system should be able to function properly within the whole range of engine speeds and irrespectively of the level of fuel supply.

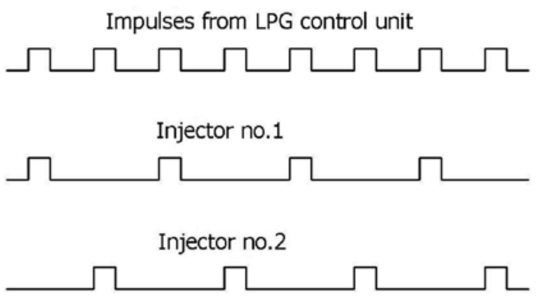

Fig. 5. Modified fourth generation gas installation injector supply diagram

Before moving on to the design phase of the modified fuel system, a simulation was performed to see how the engine would function at 5000 rpm. The simulation was based on the mathematical model discussed above. The results of the simulation are presented in Figure 6.

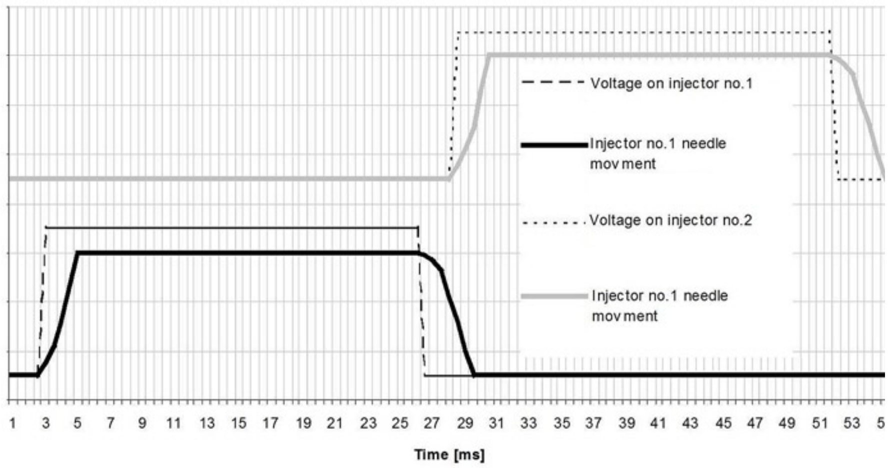

Fig. 6. Simulation of the splitter's function

In order to start the new fuel system, apart from doubling the number of injectors it was also necessary to prepare a controlling system that would split the original signal from the LPG controller into two sub-signals that powered the injectors.

The working principle of such a system should be based on a falling edge. It means that the system should firstly identify the change in voltage from high to low, and based on that information it should switch the path of the original signal, in this case the one generated by the LPG controller. The splitter shouldn't therefore change the form of the signal, but rather send it to appropriate connectors.

Knowing these general assumption, a splitter model was prepared that based on several integrated circuits (2x 7414N, 4013N, 2x TC4422AVPA), two transistors (IRF520 N-FET 100V 8A 40W), as well as resistors, capacitors, and diodes. Everything was then placed on a special circuit board made especially for this system. All incoming and going signals go through precision connectors installed on both ends of the circuit board. The first two are used to connect the 12V power source, the next two are used to intercept the signal generated by the LPG controller. The four remaining connectors are outputs for the signals that control the LPG injectors in the modified fuel system.

This system was build and, along with the injector rail, it was then installed in the test vehicle. The test vehicle was a BMW 316i passenger car equipped with a four cylinder M40 engine (capacity: 1596 cm^3, power: 75 kW) and a sequential gas injection system, whose main elements were: ZENIT JZ controller, Zavili Zeta-S reducer, ZENIT AA-612 pressure sensor and Valterk 3Ω injectors.

The electrical installation of the splitter of the controlling signal was limited to connecting with the wires going from the LPG controller to the injectors. The fuel lines required the installation of additional distributors. The installation method is therefore non-invasive, and allows the original installation to be restored quickly, if the user is not satisfied with the new configuration.

4. Effects of the modification of the alternative fuel system on the process of fuel supply.

After installing, connecting and calibrating the modified elements, the influence of the changes on the supply process was verified. The first test drive showed a significant improvement in terms of high engine speeds. It was noticed that the doubled number of injectors contributed to reducing the loss of power at high engine speeds eliminated the switching back to the conventional, petrol fuel system.

Using an oscilloscope, the voltage was measured on the connectors of the injectors, in order to confirm if the original input is correctly split into two output signals.

The results presented in Figure 7 clearly show that the aim was achieved. The installed electric device split the signal generated by the LPG controller between two injectors that worked alternately. The positive impact of the modifications allowed for further testing: the course of the voltage for higher engine speeds.

The voltage on the injectors was measured every 1000 rpm (from 1000 rpm to 5000 rpm).

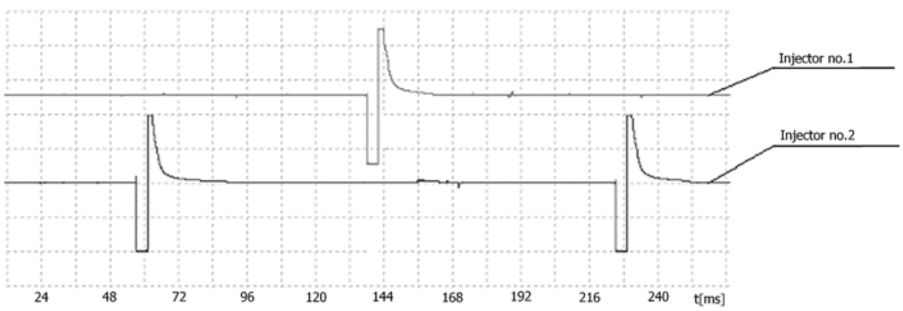

Fig. 7. Course of the impulses in the injectors of one cylinder in the modified installation; engine speed approx. 700 rpm.

The measurement was based on recording the course of the controlling signals for approximately 10 seconds, three times for each engine speed. This again was done using the oscilloscope and computer mentioned above. In each test, the signal was split correctly and the injectors supplying the same cylinder worked alternately. In the modified installation, at 5000 rpm (the speed at which the injector remained open in the non-modified installation) it is clear that the voltage on each injector drops to zero and the interval between each work cycle is sufficient for the needle valve to return to its closed position [16] (for valve 1, the loss of controlling impulse occurs at 70 ms of the measurement, while another signal occurs at 78 ms; this time is therefore sufficient for a total closure of the injector [16]).

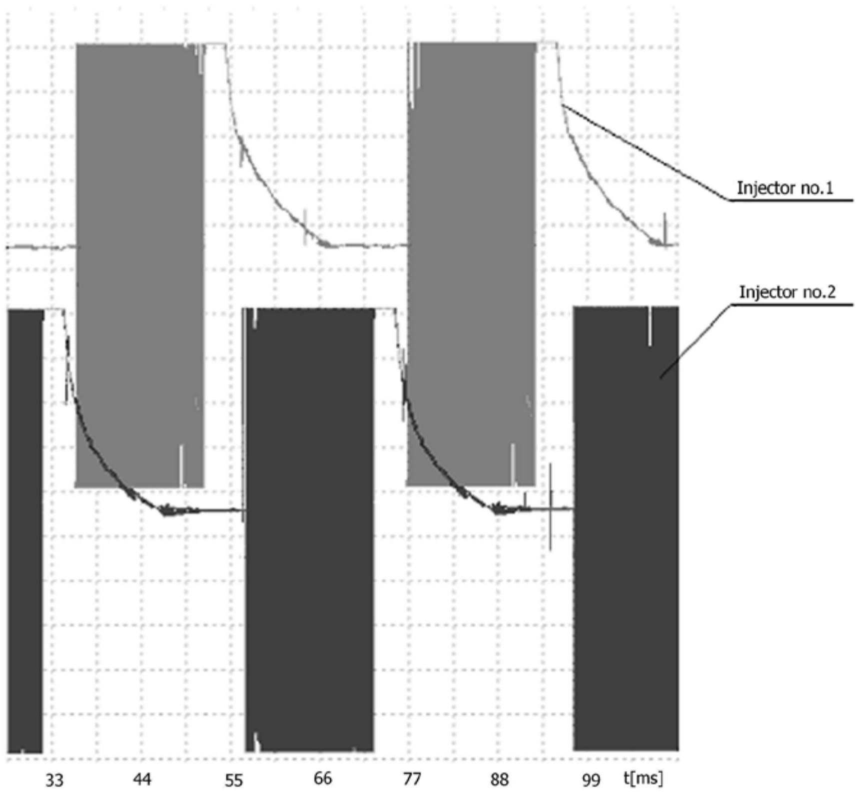

Fig. 8. Course of the impulses in the injectors in the modified installation; engine speed approx. 5000 rpm.

The doubling of the number of injectors also made it possible for the fuel system to supply the required amount of fuel for every engine speed and for each supply level (the maximum capacity was doubled). Therefore, the gas installation stopped to shut down and performed its fuel supply functions in all working conditions.

5. Summary

Poland is one of the top European countries in terms of the popularity of alternative fuels, especially LPG, and the number of vehicles powered by such fuels. Car users install LPG systems mainly due to economical reasons, accepting the numerous disadvantages of gas installations. The constant development of alternative fuel systems designs decreases these disadvantages, although it still is impossible to eliminate them completely. With the mass scale of vehicles used in transport of people and goods, even the slightest improvement of supply systems in combustion engines has a significant importance both to the economy and the natural environment.

The modification of an LPG installation described in this article has a significant impact on the process of the engine's power supply. The developed electronic unit splits the controlling signal generated by the LPG controller into two sub-signals that control the functions of the injectors on a given cylinder. This solution causes provides the engine is powered precisely at low engine speeds and low supply levels, but it also provides adequate power at high engine speeds and supply requirements. Cutting the injector work frequency in half results in lowering the thermal stress on the injectors and decreases the risk of the occurrence of magnetic saturation [13]. Owing to this, the process of dosing the fuel is characterised by a higher level of repetitiveness, and the injectors are characterised by a longer service life.

The implemented modification also eliminated the problem with the shutting down of the alternative fuel system at high engine speed and high supply. The benefits of the changes include:

- reducing the usage costs due to decreased consumption of petrol, which is a more expensive fuel than LPG;
- improving the usefulness factors of the engine, since every change of the power source causes the controlling computer (ECU) to "re-learn" the supply map, with the engine generating less power and torque [16];
- decreasing the level of harmful emissions in exhaust gasses by limiting the emission of carbon monoxide and dioxide, in line with the current trends in the automotive industry (combustion of LPG produces fewer substances that are harmful to the environment that combustion of petrol [12]).

Another advantage of the proposed solution is also the cost of the modification (calculated on the basis of the costs incurred by the author in relation to the construction and installation of the device) which is approximately 10% of the cost of adjusting a vehicle to be powered with an alternative fuel system. The cost is small, considering the advantages stemming from the improved design.

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