IDENTIFICATION OF FUEL INJECTION CONTROL SYSTEM IN A GDI ENGINE

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Abstract

In 1995 as a first in the world Mitsubishi introduced SI engine with the direct fuel injection to combustion chamber GDI (Gasoline Direct Injection). Currently such a way of providing of gasoline is applied and introduced to mass production by other companies. This solution permits to burn stratified mixtures which is rich in the region of the spark plug and very lean in more distant areas of the combustion chamber. The average mixture composition of such a mixture is very poor and often incombustible. The combustion of lean mixture to some extend permits to reduce fuel consumption but limits also the possibility of reduction of NOx by the typical catalyst. Furthermore the direct injection of gasoline to combustion chamber gives the possibility of the precise dosage in each cycle. The precise control of mixture composition is possible because the injection of the fuel takes place after closure of inlet valve, so the amount of the air in the cylinder is known. The precise dosage and the dispersion of the fuel in connected with several problems. The additional information which is provided by sensors installed on the engine is very useful to solve. Gasoline direct injection fuel systems are equipped with sensors which aren't use in standard indirect systems. These problems are described in the paper with special attention paid on the accuracy of the dosage of the fuel and all problems related with this.

Keywords: *gasoline engine, mixture composition, injector characteristic, control of volumetric efficiency*

1. The introduction

The air-fuel mixture composition has significant influence on parameters of engine run such as: fuel consumption, dynamics and engine emission. From this point of view it is essential to create proper air-fuel mixture composition for each point of its run. The estimation of the proper mixture composition is a task for the system of the control an injection of the fuel. In the history of development of electronic gasoline injection systems there are injection systems for indirect injection and direct injection systems. In the older version the indirect injection systems, called one-point injection systems, there was one injector situated centrally over the throttle. Many disadvantages of such a way of the fuelling caused the introduction of the multipoint injection. A system was equipped with individual injectors which provided fuel to the engine inlet channel over the inlet valves of individual cylinders. Currently it is the most often applied way of the fuelling of SI engine. The important disadvantage of the multipoint injection is the lack of the possibility of the combustion of very lean mixtures and the lack of the possibility of the exact control of the mixture composition, particularly in transient states. The combustion of lean mixtures to some extends gives possibilities of reducing of fuel consumption. Unfortunately, behind lean burn limit the mixture becomes incombustible and there is no possibility of their ignition and combustion. The solution is the stratification of the mixture i.e. about the flammable composition in regions of the spark plug and incombustible, and even itself air, in more distant regions of the combustion chamber. The creation of stratified mixtures is possible in the system of the direct injection of gasoline in which the fuel can be injected into the region of the spark plug in the last phase of the compression stroke before the appearance of the spark.

In the indirect injection systems where the fuel was injected during intake stroke the mass of air in the cylinder wasn't controlled in precise way. This caused that it wasn't possible to inject exact dose of a fuel and to prepare the required mixture composition, particularly during transient states of engine run. Solution of this problem is the direct-injection of petrol to the combustion chamber.

The possibility of the injection of gasoline at the end of the compression stroke caused that the engine with gasoline direct injection was chosen for development in the research project over the new method of the control the mixture composition from the cycle on the cycle [1, 3]. From among existing engines with the direct injection of gasoline systems, the engine which was produced as a first and applied to drive the passenger car was chosen for research work.

2. GDI system construction

The first stage of research work on the new method of the control with the mixture composition included the identification of the fuel and control system of the gasoline direct injection (GDI) engine from Mitsubishi Carisma. On the basis of the technical documentation [2] and the recognition done in the car the diagram of the fuel injection system and the control of it was elaborated. The diagram contains all elements including sensors (Fig. 1).

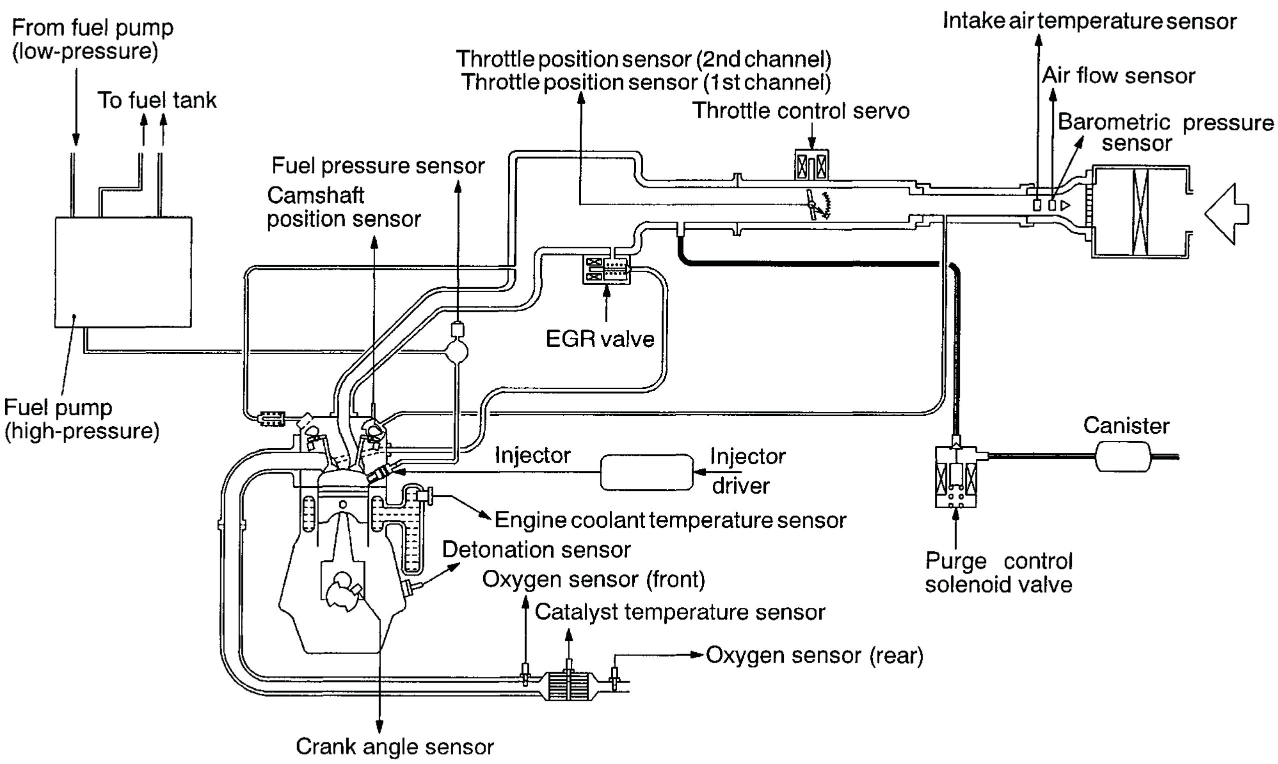

Fig. 1. The diagram of GDI system from Mitsubishi Carisma

In the system there are many similar components as in many others systems applied in standard SI engines. Nevertheless there are some differences which are presented in the paper. A basic difference is injector construction. Thanks to the injectors position the fuel can be injected directly to the combustion chamber into regions of the spark plug. Such solution requires the use of special injectors. The injection of the fuel must be realized in a short time. In order to inject the fuel in short time and simultaneously to minimize the influence the cylinder pressure the dose of gasoline should be injected under high, all the time controlled, pressure (4.8-6.0 MPa) [2]. The time of the injection of the fuel should be shorter than in the systems of indirect injection and it is possible to inject the fuel in suitable phases of the engine cycle. This condition can be realized by injectors controlled in a special way. The task is realized by special power driver which is able to very fast switching on the injector. The time of reaction is below 0,5ms. It is possible to achieve such a fast response because of large current caused by the increased voltage (to approx. 100V). The power driver as a separate device controls the current of injectors. An input signal for the driver is the voltage signal where 0V (the short circuit to the mass) is the base.

The second feature which distinguishes the direct injection from the indirect injection system is the identification of phases of the engine cycle for individual cylinders. It is realized by two sensors:

- positions of the crankshaft (crank angle sensor - CAS),
- positions of the camshaft (camshaft sensor - CS).

The identification of phases is necessary in order to deliver the fuel to individual cylinders in due time (e.g. at the end of the compression stroke).

3. The program of research work and the engine examination

The main objective of the identification of the direct injection system is the development of the method of the injection control. The method which gives the possibility of cycle by cycle control of injection is dedicated to ensure a proper mixture composition in each cycle. For this purpose it is necessary to know the characteristics of the flow of injectors used in the system.

The research program is as follows:

- identification of the characteristics of the crankshaft position and the phase of the cycle unit,
- identification of phases of the cycle determined by factory, in which fuel injection takes place,
- determination of the mass flow characteristics of the injector.

The identification of the characteristics of the crankshaft position and the phase of the cycle unit is based on simultaneous registration of the crankshaft and the camshaft position signal, as well as ignition coil signals and then converting of the time scale to the scale with crankshaft angle. On the basis of spark timing and technical documentation [2] it is possible to determine the beginning of the cycle for each cylinder of the engine. The determination of the determined by factory cycle phases during which the injection takes place is the next step in the identification of the control system. The aim of the tests is to answer the questions: in which phase of the cycle the injection determined by factory takes place as well as what conditions should be ensured to prepare the characteristics of the injector. It demands simultaneous recording of the signals from injection and signals determining the position of the crankshaft and camshaft at different engine operating points (both stable and transitional). The measurements and analysis of the signals determined injection timing (TDC before intake stroke will be the base). Determination of the injector characteristics is be based on simultaneous measurement of mass loss of fuel from the tank, signal recordings from all the injectors and fuel pressure signal as well as registration of the signal which determine the phase of each cycle. These measurements are made for stable engine run at the highest possible speed and for different engine loads.

4. The test stand

The tests were planned and performed on 1.8 litters Mitsubishi Carisma GDI engine. The engine was installed in the vehicle and the test was conducted on a chassis dynamometer. Measurements of electronic control signals were made with the use of PC equipped with data acquisition system Gage type CompuScope 8380. The signals from the engine have been gathered and send to PC by the interface, which was designed and built in Technical University of Radom. The interface allows measurement of all signals from the engine control system and the control of the injectors and ignition coils with the use of external signals. The interface is designed to send external signals to the controller of injection and ignition.

The second very important element of the test stand was a system for measurement of fuel consumption which is necessary to prepare the characteristics of the injector. Construction of the special stand for measurement of the fuel delivered to the injectors under high pressure through mechanically driven pump from the camshaft and injected into the combustion chamber would be difficult and complicated. Therefore, the characteristics of the injector are based on measurements of fuel consumption during normal engine operation. For this purpose tank removed from the car was put on the scale with a resolution of one gram. The scale measured the loss of fuel during the stable run of the engine. The original fuel system differs from the fuel system used in the tests only the length of the pipe connecting the engine with fuel tank.

5. Test results

As a result of research and analysis of technical documentation the method of identifying the location of the crankshaft and the phases of the cycle in each cylinder of the engine was developed. Fig. 2 shows the phase of the cycle for each cylinder of the engine on the background of crankshaft position (CAS) and camshaft (CS) signals. The axis with the engine crankshaft position is calibrated in degrees from the beginning of the cycle for the first cylinder, i.e. zero degrees are the start of the cycle and the piston is in TDC before intake stroke.

Analyze of the sensor signals clearly shows the phase of the cycle after the second observed slope. Tab. 1 shows the angle position of the crankshaft in the engine cycle for each cylinder. In order to determine the position of the crankshaft from the start of the cycle in the cylinder it was observed camshaft signal (CS) and crankshaft signal (CAS).

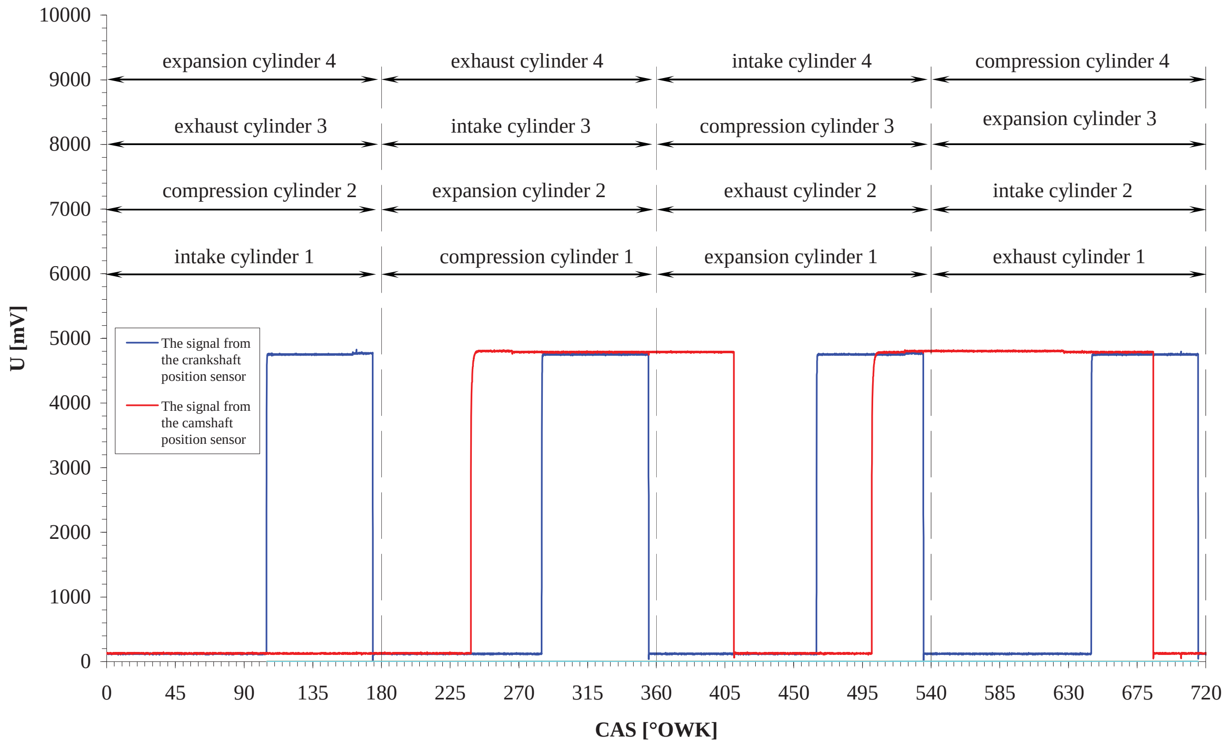

Fig. 2. Phase cycles for each Mitsubishi Carisma GDI engine cylinder and the sensor signals: crankshaft position and camshaft position [own research]

When the slope of any of these signals is visible the state of the signal from the camshaft sensor should be remembered. After the re-emergence of the slope of any of these signals it is possible to determine the crankshaft position according to Tab. 1. CS_{-1} in the table - is a signal from the camshaft during the previous slope of any of the signals.

Tab. 1. Identification of crankshaft angle from the beginning of the cycle for each Mitsubishi Carisma GDI engine cylinder

sensor signal		crankshaft angle /from the beginning of engine cycle/			
CS_{-1}	CAS	1st cylinder	2nd cylinder	3rd cylinder	4th cylinder
N	↑	105	285	645	465
N	↓	175	355	715	535
N	N	240	420	60	600
↑	↑	285	465	105	645
W	↓	355	535	175	715
W	N	410	590	230	50
↓	↑	465	645	285	105
N	W	500	680	320	140
↑	↓	535	715	355	175
W	↑	645	105	465	285
W	W	685	145	505	325
↓	↓	715	175	535	355

In the table the states of the signals from the sensors were defined as follows:
N - low,
W - high,
↓ - slope edge (change from high to low),
↑ - rise edge (change from low to high).

The next step was the evaluation in which of the phases of the engine cycle the fuel is injected into the combustion chamber. For this purpose the control injector signals and the position of the engine crankshaft and camshaft signal were registered. This registration was performed in a number of different points of engine operation such as idle, various loads and speed for the stable and dynamic conditions (rapid acceleration and slowing down). One of the registrations shows Fig. 3. This is a part of the registration of steady state operation of the engine while driving on the third gear at a speed of about 80km/h. For this conditions there were observed injections during three strokes: intake, compression and expansion. During others measurements the injections were also observed in the same engine strokes but due to the limited volume of the publications the results are not presented.

The characteristics of the mass flow of injector are based upon the measurement of fuel consumption when driving a car on a chassis dynamometer. Each measurement of fuel consumption lasted 150 s. At that time loss of the fuel from the original fuel tank located on the test stand was measured. The loss was measured with a resolution of one gram. At the same time control signals from all injectors were recorded. During the measurement constant speed and constant engine was maintained.

With the use of the software which was elaborated to analyse the results of measurement, injection timing and the end of injection were determined. Then the total number of fuel injections and the average time of injection were calculated. After completion of the injection timing charts some measurements were eliminated. Fig. 4 shows such a case. Other measurements, which were performed for 150s were used to prepare the characteristics of fuel mass flow. Such measurement shows Fig. 5. The average values of injection time Tw measured within 150 seconds are given

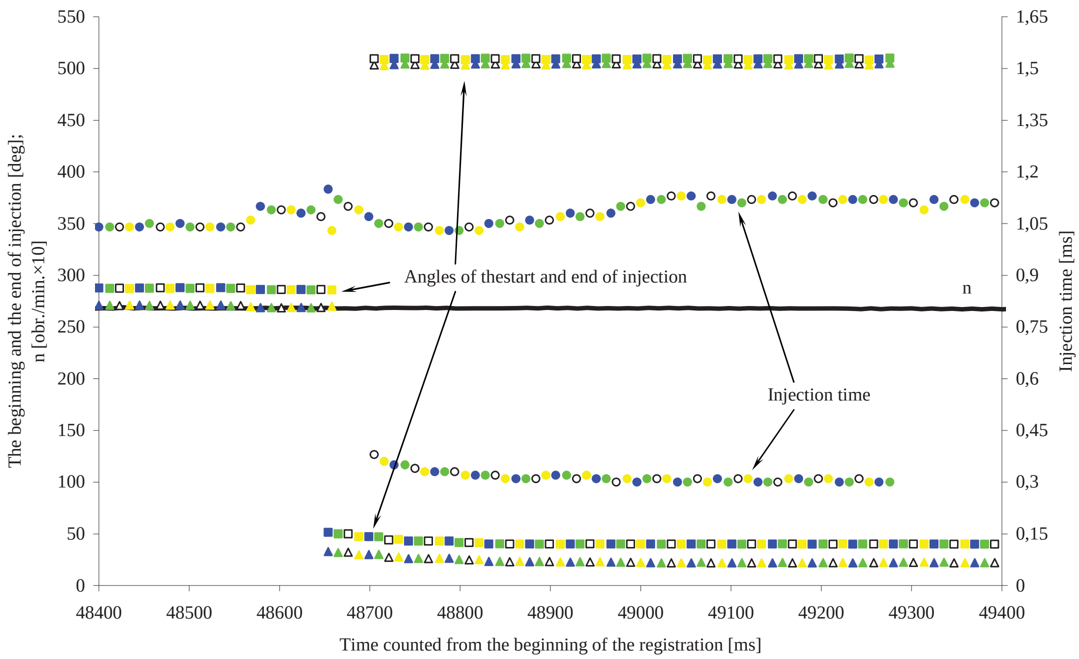

Fig. 3. The beginning and the end of fuel injection determined by factory Mitsubishi Carisma GDI engine control system [own research]

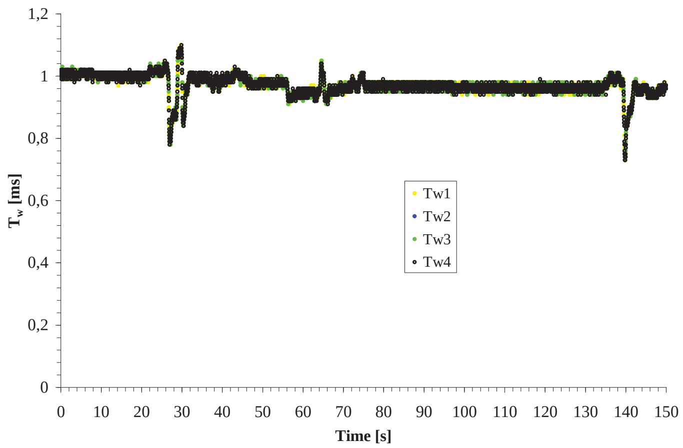

Fig. 4. Sample measurement without maintaining of the constant injection time - 150s. This measurement was rejected [their research]

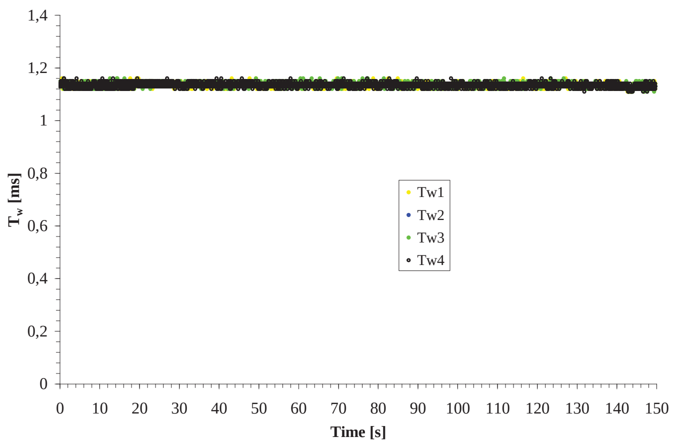

Fig. 5. An example of measurement in which the injection time was maintained constant by the 150s, this measurement was used to produce the characteristics of the injector [own research]

in Tab. 2. The table also presents: m_p - mass of the fuel tank before the measurement, m_e - the mass of the fuel tank after the measurement, m - fuel loss during the measurement, l_w - total number of injections in all engine cylinders during the measurement and weight of fuel per injection m_F - which is calculated by (1):

$$m_F = \frac{(m_k - m_p)\cdot 1000000}{l_w}. \tag{1}$$

Tab. 2. The results of measurements of mass flow of the fuel in Mitsubishi Carisma GDI engine

File name	T_w	m_p	m_e	$m=m_p$-m_e	l_w	m_F	File name	T_w	m_p	m_e	$m=m_p$-m_e	l_w	m_F
a1	0.520	18.117	17.833	0.284	39402	7.208	b4	0.975	14.21	13.826	0.384	29099	13.196
a2	2.279	16.211	15.04	1.171	40378	29.001	c1	0.972	20.713	20.342	0.371	28443	13.044
a3	1.389	14.739	14.013	0.726	40226	18.048	c2	1.166	19.94	19.511	0.429	27641	15.520
a4	3.112	20.023	17.931	2.092	53590	39.037	c3	0.869	19.34	19.016	0.324	27101	11.955
a5	0.566	17.526	17.469	0.057	7485	7.615	c4	1.154	18.448	18.048	0.400	27555	14.516
a6	0.840	17.265	17.018	0.247	22428	11.013	c5	1.135	18.03	17.631	0.399	28502	13.999
a7	0.659	16.823	16.522	0.301	32930	9.141	c6	1.396	17.515	17.023	0.492	27979	17.585
a8	0.814	16.2	15.572	0.628	55495	11.316	c7	1.592	16.918	16.396	0.522	27736	18.820
a9	0.575	15.151	15.093	0.058	7502	7.731	c8	1.968	16.242	15.58	0.662	27490	24.081
a10	0.559	14.925	14.866	0.059	7485	7.882	c9	1.063	15.048	14.793	0.255	19194	13.285
a11	0.493	14.652	14.483	0.169	24760	6.826	c10	1.367	14.689	14.349	0.340	19418	17.510
a12	0.654	1.896	1.276	0.620	58854	10.535	c11	1.679	14.34	13.951	0.389	19420	20.031
b1	0.538	15.19	15.083	0.107	14729	7.265	c12	2.039	13.782	13.254	0.528	19392	27.228
b2	0.653	14.769	14.507	0.262	29144	8.990	c13	1.043	12.512	12.334	0.178	13438	13.246
b3	0.774	14.519	14.204	0.315	29036	10.849	c14	1.538	12.248	12.003	0.245	13000	18.846

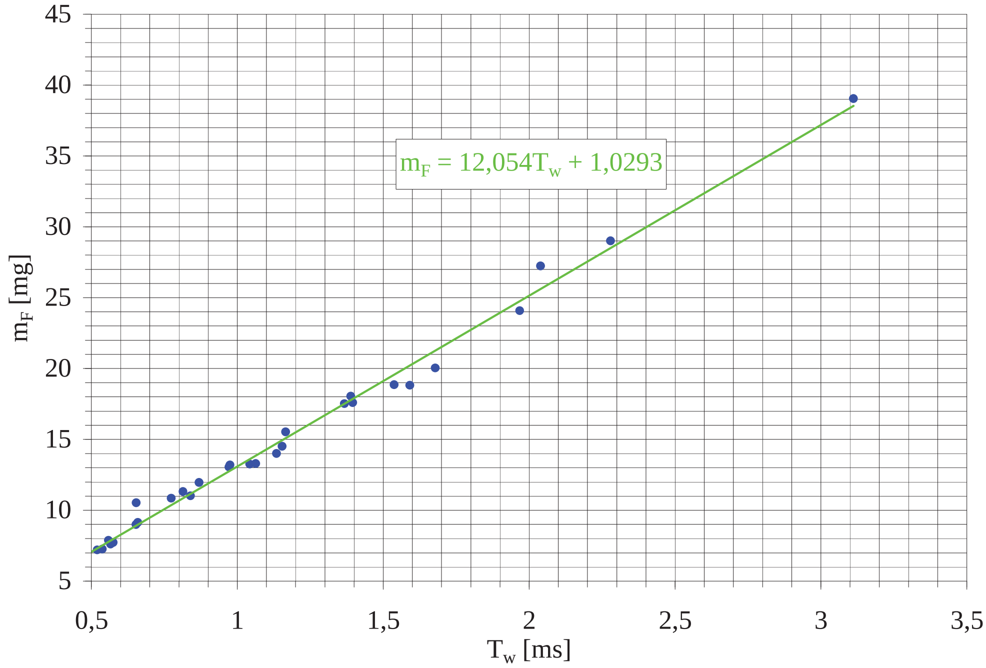

Fig. 6. Characteristic of injector of Mitsubishi Carisma GDI engine [own research]

The obtained measurement results are presented in the chart was approximated with a line and is described by the equation. This way the injector characteristic of direct injection gasoline Mitsubishi Carisma engine was prepared.

6. Conclusion

1. Direct injection system demands identification of the phase of the cycle in each cylinder, which is possible after the second slope of any of the signals: CAS or CS.
2. Direct injection takes place in intake, compression and expansion strokes.
3. Characteristics of the examined injector are linear.

References

[1] *Rozwój sposobu sterowania składem mieszanki z cyklu na cykl na przykładzie silnika benzynowego*, sprawozdanie z realizacji projektu badawczego MNiI nr 4T12D00927 realizowanego w Politechnice Radomskiej, Radom 2007.

[2] Workshop Manual - electrical wiring supplement CARISMA 2001, Mitsubishi Motors 2009.

[3] Wołczyński, Z., *Metoda sterowania składem mieszanki w silniku benzynowym*, rozprawa doktorska, Politechnika Radomska, Radom 2005.