EXPERIMENTAL STUDY IN GASOLINE ENGINE INJECTOR PERFORMANCE

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Abstract. The paper describes the methodology and results of evaluation of the flow capacity of the fuel injectors in the automobiles, equipped with spark ignition, port fuel injection engine. Automobiles, which are designed to work with regular gasoline, can be adapted for use of blend of bioethanol and gasoline, for instance, fuel E85. Certain components have to be evaluated for their compatibility with E85. The fuel injectors of the adapted engine have to supply a larger amount of E85 fuel, comparing with the operation with gasoline. The studies were conducted on two unmodified automobiles. The tests were performed on a roll type chassis dynamometer, set in constant speed mode. The measurements were done using a multichannel oscilloscope and piezoelectric microphone. Combined electrical and acoustic injector diagnostic methods were used and are thoroughly explained. The obtained results confirm the efficiency and robustness of the chosen diagnostic method. The results of the automobile testing confirm the necessity of the injector flow evaluation before converting the automobile for use of E85 fuel.

Keywords: spark ignition engine, gasoline, ethanol, injector, injector flow, injector duty cycle.

Introduction

The current fleet of automobiles in Europe are using an unsustainable source of energy – gasoline or diesel fuel [1]. At the early stage of development of automotive industry, the choice to use gasoline instead alcohol fuel was made. Explanation for this outcome in the U.S. has been associated to price relationships, market structures, commercial arrangements and practices combining the interests of oil, chemical, and automotive industry, linking large corporations of that time, such as Standard Oil, Du Pont and General Motors [2; 3]. Brazil is showing an example to the rest of the world that by applying a certain amount of will and effort, sustainable transportation industry can be created. In April 2008, ethanol became the second most consumed liquid fuel used for transportation purposes in Brazil after diesel [4]. This achievement demonstrates the current trends in fuel consumption in Brazil and reflects the increasing importance of ethanol in the available fuel mix. It is also an outcome of the establishment of flex-fuel technology as the main platform for the Brazil national automobile industry [5].

The Directive 2009/28/CE "On the promotion of the use of energy from renewable sources" of the European Parliament and of the Council sets a target of 10 % for energy from renewable sources in transport must be reached in 2020 by all Member States [6]. Current implementation of the commercial gasoline standard EN228 in Latvia defines use of 5 % ethanol in gasoline blend as standard fuel for automobiles with spark ignition (SI) engines. Most of the modern SI equipped automobiles are built to operate with such fuel blend. The fuel blend, known as E85, contains up to 85 % of anhydrous ethanol and 15 % of gasoline, depending on the season. Major automobile producers offer versions of automobiles, compatible with E85. Availability of such automobiles, known as FFV or Flexible-fuel vehicles, depends on the market. Aftermarket solutions exist, allowing converting the production standard SI equipped automobile to use E85 instead of gasoline [7; 8]. Before installing and use of such adapter, assessment of the automobile fuel system components must be done. From the safety point of view material compatibility to ethanol must be verified [9]. Ethanol has different physical properties comparing to gasoline. The benefits of E85, such as faster flame rate, higher resistance to detonation and charge cooling effect do not compensate the lower combustion heating value and vapour pressure. The fuel consumption of E85 is higher, comparing to gasoline. Depending on the engine design and conditions of use, the difference in fuel consumption can reach 26-35 % [10]. Fuel conversion kits work by altering and extending the original fuel injector opening pulse width, supplying larger fuel amount to the engine. It is only possible, if there is a reserve left in the injector duty cycle. Theoretical aspects of the operational parameters of automobile running on ethanol-gasoline blends were described by Aboltins et al. 2010 [11]. There is a lack of research results on the conversion adapter design, requirements and testing. This study focuses on creation of the robust methodology for evaluation of production installed gasoline engine injector capability to supply a sufficient amount of fuel in case of vehicle conversion for E85 use.

Materials and methods

The properties of the production standard fuel injectors of two different automobiles were studied. Both test automobiles were equipped with the atmospheric port fuel injection (PFI) SI engines. The main specifications of the test automobiles are presented in Table 1.

Table 1

Main specifications of test automobiles

Model	**Volkswagen Passat**	**Renault Twingo**
Identification number	WVWZZZ3BZWE103686	VF1C068AE28944909
Date of production	27.07.1997	30.04.2003
Engine	Type ADR, 4-cylinder 20-valve	Type D7F 702, 4-cylinder 8-valve
Compression ratio	10.30	9.65
Displacement volume	1781 cm^3	1149 cm^3
Engine control system	Bosch Motronic M3.8.2	Siemens Sirius 32
Fuel injector type	Bosch EV1 028150444	Siemens Deka 873774
Fuel injector resistance	12.6 Ω	14.7 Ω
Gearbox	Type DHZ, 5-gear manual	Type JB1 517, 5-gear manual
Gear ratios	Final drive 4.111; 4^{th} gear 1.029	Final drive 3.866; 4^{th} gear 1.034

The tests were performed using gasoline of EN228 standard, purchased in Statoil fuel station. The main properties of the test fuel were obtained from the certificate, provided by the fuel supplier – density 740 $kg{\cdot}m^3$ at 15 ºC; research octane number (RON) 95.4; motor octane number (MON) 85.9; ethanol content 4.8 %.

In order to recreate driving conditions, the vehicles were placed on the roll type eddy-current chassis dynamometer Mustang MD1750. Testing was performed in wide open throttle (WOT) mode. The vehicle gearbox was set in the 4^{th} gear. The dynamometer was set in constant speed mode. The testing speed was increased in steps, allowing increase of engine rotation by 500 min^{-1} at each step. The testing engine speed range was from 1000 to 5000 min^{-1}. Air and fuel temperature was 18 ºC. To decrease effects of the engine control unit (ECU) fuel trim adaptation, ECU memory was reset before each test drive. Each test drive was repeated 5 times and the average value used as the result.

Measurement of the injector opening time and opening and closing delay was performed by combining electrical and acoustic diagnostic methods. Multiple channel portable oscilloscope PicoScope 3423 was used for current and voltage measuring and data recording. To limit voltage within the working range of the oscilloscope, potential divider was used. Oscilloscope earthing was connected to the test automobile chassis.

Current measurement was performed by measuring the voltage drop on the resistor, switched in series in the electrical circuit of the injector - power feed connection. The oscilloscope was isolated from the automobile chassis earth during current measurement.

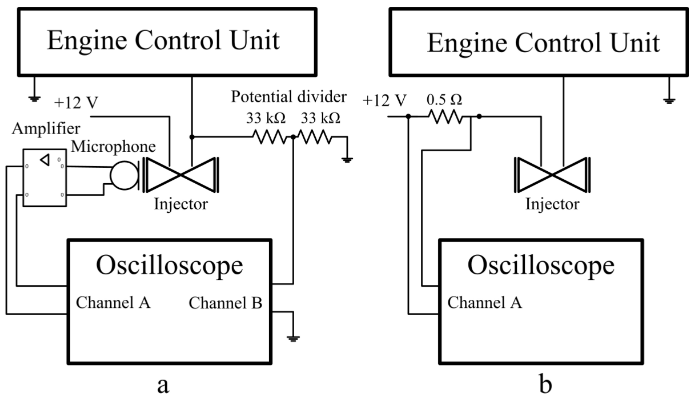

Fig. 1. **Principal connections of the test setup:**
a – voltage and acoustic measurement; b – current measurement

Acoustic diagnostic was performed using Steelman CE 06600 tool. A piezoelectric microphone was fixed on the injector body. Amplifier output was connected to the oscilloscope input channel.

Simultaneous measurement of voltage and acoustic signal allowed determining physical opening and closing moments. Principal connections of measurement setup are presented in Fig. 1.

Results and discussion

Characterizing curves of injector control are presented in Fig. 2. The voltage curve of both test subjects corresponds to the typical voltage type injector control system, which fits the description by DeGrace and Bata 1985 [12]. When the automobile antitheft lock is in the "ignition on" position, the injector coil is constantly supplied by battery feed. ECU injector driver controls injector opening by earthing the other end of the injector coil. Voltage drop to the level within 0.5-0.7 V can be seen at the point A in Fig. 2a and Fig. 2b. The current flow through the injector coil causes a magnetic field to build around the coil winding. The rising magnetic field induces counter voltage in the coil winding, which acts as the resistance and can be seen in slight rise of the voltage. When the magnetic field becomes intense enough to overcome mechanical resistance of the injector valve mechanism, the valve needle starts to move towards open position. Movement of the valve needle through the magnetic field inducts voltage in the coil winding. The effect can been seen as a slight bent in the current curve, Fig. 2b, point B. Movement of the valve needle continues until it reaches open position, which is characterized by the clicking noise, detected by the microphone and shown as a sharp rise of the noise level at the point B, Fig. 2a and Fig. 2b. This is the moment of effective valve opening. Effective valve opening can be detected by the visual method, which requires expensive high-speed camera equipment, as discussed in the research of Padala et al. 2012 [13]. It can also be done using the acoustic method, as suggested by the authors of this paper. In opposing to the combined electrical/acoustic method, the visual method is not applicable for detecting of the injector valve opening in unmodified production engine. Injector closing is initiated by the ECU by stopping of earthing one end of the injector coil winding. This moment is shown at the point C, Fig. 2, a and Fig. 2, b.

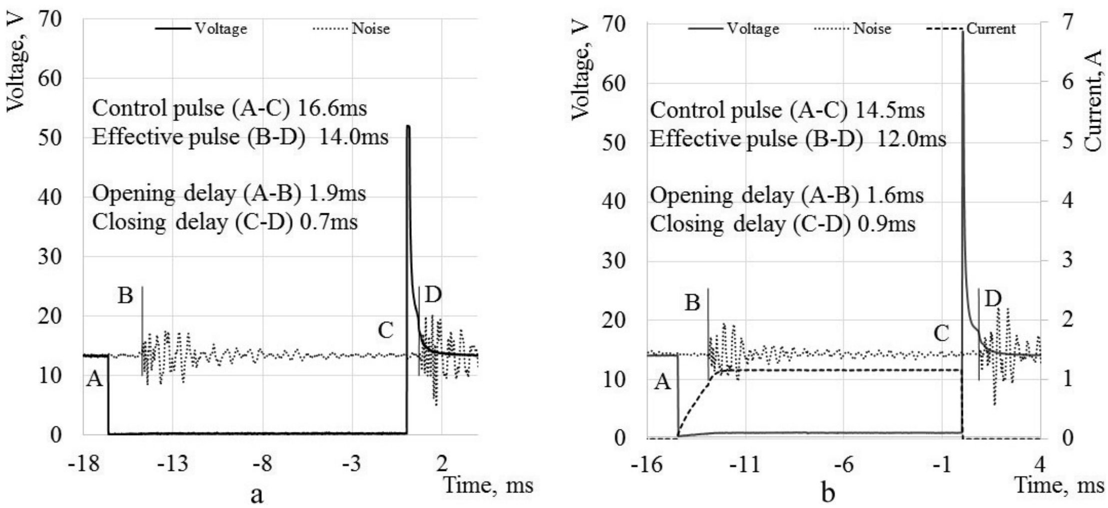

Fig. 2. **Characteristic curves of the injector control:** a – Renault Twingo; b – Volkswagen Passat

This action is followed by rapid rise of the coil voltage, caused by the coil winding acting as the inductor to resist the change of the current and using the stored magnetic energy. To prevent damage of the control driver and to slow the injector valve closing, the diode is used in the ECU injector control circuit to limit and recycle flyback voltage. Slowing of the injector valve closing is necessary to avoid damage of the valve seat and prevent uncontrolled valve needle fluctuations, and ensure linear dynamic flow parameters [12]. The moment of closing of the injector valve is shown at the point D, Fig. 2a and Fig. 2b. It is characterized by the specific voltage drop pattern but the exact moment of closing is marked with the sharp rise of the noise level. The interval from the points A to C is the control pulse width. Effective pulse width, when the fuel is actually injected, lays between the points B to D. The opening delay was larger than the closing delay, and the delay time was constant in the tested engine speed and control pulse width range for both test subjects. The injector control pulse time is presented in Fig 3.a. The curves marked with A95 show dependence of the actual measured effective pulse width on different engine rotation speed conditions for both test subjects, running on gasoline. The curves marked with E85 are calculated from the gasoline effective pulse curve values, by increasing the pulse width by 33 %. This is a typical increase in fuel volume consumption, when the engine, built for operation on gasoline, is running on E85 fuel [10]. As the engine rotation speed increases, less time remains for each injection cycle. The curve of the camshaft rotation cycle time in Fig. 3a marks the line beyond which further increase of the injector opening time is not possible. If the ECU strategy is to close and open the injector at each cycle, the injector opening and closing delay plays an important role. Effective injector opening time can be calculated by the following equation:

$$P_E = P_C - d_o + d_c, \tag{1}$$

where P_E – effective pulse width, ms;
P_C – control pulse width, ms;
d_o – opening delay, ms;
d_c – closing delay, ms.

Maximal control pulse width is determined by the following expression:

$$P_C \le C_C - d_c, \tag{2}$$

where C_C – camshaft rotation cycle time, ms.

Camshaft rotation cycle time in ms can be calculated by the following equation:

$$C_C = \frac{60}{0.5 \cdot n} \cdot 10^3 = \frac{12 \cdot 10^4}{n}, \tag{3}$$

where n – engine speed, min^{-1}.

Fig. 3, a shows the calculated effective curve for the test subject Twingo. It is shown, that theoretically needed effective opening pulse width for E85 fuel exceeds the available cycle time at the engine speed above 4380 min^{-1}. Instead of following the calculated pulse width values, the injector opening pulse width curve will follow the line marked “Available pulse width”, according to the expressions (1) and (2). From Fig. 3, a graph it can be seen that the injector flow rate of the test subject Renault Twingo is unsuitable for use of E85 fuel in the available engine speed range. The flow rate of the injectors of the test subject VW Passat is acceptable for use of E85 fuel.

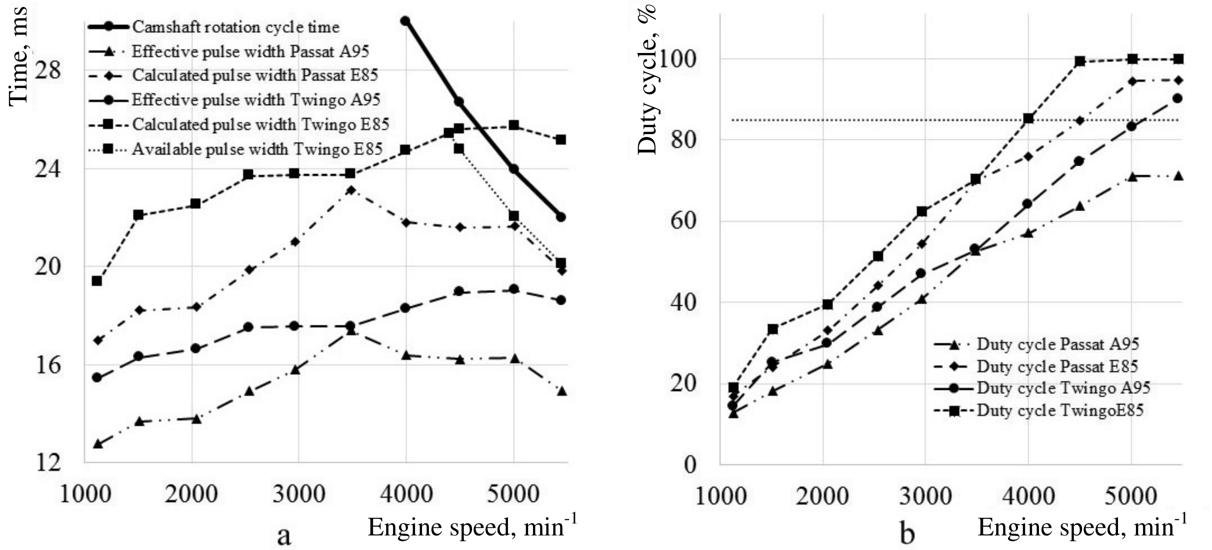

Fig. 3. **Operational curves:** a – injector pulse time; b – injector duty cycle

Another way of evaluation of the injector capacity is to express relation of the control pulse width and available cycle time as percentage, designated as the duty cycle. The following equation can be used:

$$D_C = \frac{P_C}{C_C} \cdot 100; \tag{4}$$

where D_C – duty cycle, %.

The actual duty cycle curves for both test subjects using gasoline (A95) and calculated duty cycles for E85 fuel are presented in Fig. 3b. It is a common practice not to exceed 85 % of the injector duty cycle, to leave sufficient duty cycle reserve for injector aging or contamination compensation. From the graphs presented in Fig. 3b it can be noted, that the duty cycle for the test subject Renault Twingo exceeds 85 % when the engine is running on gasoline. The calculated duty cycle for Renault Twingo using of E85 fuel shows that the injector duty cycle reaches 100 % at the engine speed above 4380 min^{-1}. For the test subject VW Passat the injector duty cycle exceeds the recommend value of 85 % at the engine speed above 5000 min^{-1}.

Conclusions

1. Fuel injector opening and closing delay can be detected using the proposed combined electrical and acoustic analysis.
2. Opening and closing delay of the injector is constant irrespective of the opening pulse width.
3. Production standard gasoline fuel injector flow rate can be insufficient for E85 fuel and must always be tested before converting a gasoline vehicle to use of E85.
4. The injector flow rate of the tested automobile Renault Twingo is insufficient for use with E85 fuel.
5. The injectors of the tested automobile Volkswagen Passat have the necessary flow rate but lack reserve duty cycle capacity if used with E85 fuel in high load conditions at the engine speed above 5000 min^{-1}.

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