The use of reusable fuel injection with the aim of improving the economic and environmental performance of the diesel engine

E A Savastenko\textsuperscript{1}, A A Savastenko\textsuperscript{1}, E V Gorbachevskiy\textsuperscript{1} and V A Markov\textsuperscript{2}

\textsuperscript{1}Moscow Automobile and Road State Technical University (MADI), 64, Leningradsky ave., Moscow, 125319, Russia
\textsuperscript{2}Head of the Piston Engines Department, Bauman Moscow State Technical University, 5, 2-a Baumanskaya str., Moscow, 105005, Russia

E-mail: e.d.u.a.r.d@inbox.ru

Abstract. The current trend in the development of motor-and-tractor diesel engines imposes tough requirements on fuel equipment and the fuel supply process. The implementation of it is difficult to combine with the requirements of reducing heat generation at the initial stage of combustion and the rate of pressure increment to reduce exhaust emissions and engine noise. A decrease in the duration of the injection process and an increase in the volumetric feed rate lead to a growth in the cycle dynamism factor and an increase in the operation noise. This scientific article discusses the use of multiple injection of fuel in a diesel engine to reduce the emission of nitrogen oxides, smoke and particulate matter by improving the heat transfer processes, the mixture formation and, as a result, heat generation. Low exhaust gases toxicity and smokiness values are achieved.

1. Introduction

The development of engines with promising energy and environmental parameters requires the development of new options for the fuel supply system for various diesel models \cite{1, 2}. In this regard, important tasks are to ensure injection pressure up to 200MPa and higher \cite{3, 4}; as well as regulating the shape of the leading edge of the injection characteristics \cite{5, 6} and organizing the distribution of fuel in the combustion chamber \cite{7, 8}. The required law of fuel injection for any engine operation mode is formed by changing the control pulse duration and the pressure in the fuel accumulator. It also depends on the wave phenomenon that occurs in the high-pressure line and has a significant effect on the fuel injection during multi-stage injection \cite{9–12}.

These materials are based on experimental data obtained by masters and graduate students of RUDN University and according to a mathematical model developed at Moscow State Automobile and Road Technical University (MADI) \cite{1, 13}. The experiments were carried out on a single-cylinder diesel engine equipped with battery-powered fuel equipment (CR). In the course of research, tests were carried out on various methods of supplying fuel to the diesel combustion chamber. In particular, several preliminary injections of fuel were used in relation to the main one with varying injection angles, injection pressures and angular intervals between pre-injections.

2. Experimental study of reusable fuel injection

The processing of experimental data consisted in analysis of the dependence of economic, toxic, noise indicators of the diesel engine, as well as smokiness and their compliance with modern requirements for exhaust emissions. A diagram of the multi-stage injection characteristic is shown in Fig. 1.
Figure 1. Stepped injection characteristic ($t_{c.v.2} –$ control voltage time of pilot injection $n_2$; $t_{c.v.1} –$ control voltage time of pilot injection $n_1$; $dº_1 –$ delay between pilot injection $n_1$ and basic (main) injection; $dº_2 –$ delay between pilot injection $n_2$ and pilot injection $n_1$) [14].

Five injections were studied with different amounts of fuel (different times of the control voltage impulse ($t_{c.v.}$)) and different delays between the pilot and main injections for illustrating the effect of pre-injection (pilot injection) on the indexes of the diesel engine exhaust gases emissions. The experiment was carried out at a constant frequency of the crankshaft ($n = 2000$ rpm) and injection pressure ($P_{inj} = 55$ MPa).

Emission indexes of the diesel engine exhaust gases are shown in table 1. Graphs of nitric oxides ($NO_x$) emissions, specific effective fuel consumption ($g_e$), soot and noise characteristics of the diesel engine are shown in figure 2.

Table 1. Emissions indexes from engine exhaust gases with factory settings

| $g_e$ (g/kW·h) | $NO_x$ (g/kW·h) | Soot (g/kW·h) | HC (g/kW·h) | CO (g/kW·h) | Noise (dB) |
|---------------|-----------------|---------------|-------------|-------------|------------|
| 305,5         | 1,5             | 0,72          | 0,71        | 4,8         | 84,9       |

Figure 2 shows that the optimal delay between the pilot injection $n_1$ and the main injection is $dº_1 = 6^\circ$ of crankshaft rotation. The results of the first test showed both positive and negative points: soot indicators decreased by almost 40 %, HC indicators reduced by almost 16 %, CO indicators decreased by almost 17 %, specific effective fuel consumption reduced by 3 %. But negative phenomena appeared too: $NO_x$ roused by 12 %, the noise of the combustion process increased slightly by 2 %.

This allows making an electronic control unit with a readout board that reads diesel engine data in real time and changes certain parameters set by the operator in the program. The pressure in the cylinder of the diesel was recorded by a piezoelectric sensor. Bosch ESAS250 gas analyzer was used for gas analysis, as well as equipment for determining the noise indexes of engines.

We made some changes: $P_{inj} = 67.5$ MPa and injection angle of the main portion of fuel ($\varphi = 3.5$ crankshaft rotation after TDC) for emissions reduction of solid particles HC, soot and NOx.

Figure 3 shows that the results of tests conducted with the changed injection pressure and the injection angle of the main portion of the fuel can be concluded that there were no large changes and the change in the injection angle of the main portion of the fuel did not give results. The indexes of CO and solid particles of CH remained unchanged, and some indicators increased: $NO_x$ increased by almost 20 %. This is mainly due to the fact that because of the increased injection pressure, the fuel oxidizes and burns better, since the dispersion of fuel atomization has increased, which in turn leads to bigger speed of pressure rise rate in the cylinder. As a result of the injection grows, as could be expected, the smoke level decreased by almost 100 %, to 0.2 g/kW·h, which is a significant advantage of the fact that the injection pressure is increased.
Figure 2. One pilot injection $n_1$ with various delays of the crankshaft rotation angle relatively to the main injection. $4^\circ$, $6^\circ$, $8^\circ$, $16^\circ$, $30^\circ$ – delay angles between pilot and main injections in angles of the crankshaft rotation
Figure 3. Influence of $t_{c,v}$ and delay time between the pilot injection $n1$ and the main injection on ecological, economic and noise indicators of the engine: A – Delay between the pilot and the main injection is 6° of crankshaft rotation. Fuel pressure in the battery is 55 MPa; Start of the main injection is 3.5° of crankshaft rotation. B – Delay between the pilot and the main injection is 6° of crankshaft rotation. Fuel pressure in the battery is 55 MPa; Start of the main injection is 1.5° of crankshaft rotation. C – Delay between the pilot and the main injection is 6° of crankshaft rotation. Fuel pressure in the battery is 67.5 MPa; Start of the main injection is 3.5° of crankshaft rotation.
Due to the high NO\textsubscript{x} emissions, the exhaust gas recirculation rate was increased by 8 %. NO\textsubscript{x} rates have declined, but soot emissions have increased. Thus, the optimal settings were chosen: the delay between the pilot injection and the main one, the control voltage time (figure 4), where the highlighted line is the optimal dependence of the pressure in the cylinder on the nozzle needle lift; the angle of injection of the main fuel charge. The characteristic of the pressure change in the cylinder was chosen on the basis of the following considerations: the characteristic of the pressure change in the cylinder should be as flat as possible, without sudden changes in pressure. Also Figure 4 shows the optimal dependence of the heat generation rate on the nozzle needle lift, where two peaks are clearly traced, which characterize the pilot injection and the main one, respectively.

![Figure 4. Influence of the needle lift height on pressure in the cylinder.](image)

3. Conclusions

The use of the multiphase injection characteristic in the diesel engine reduces indicators of emissions with exhaust gases due to more improved mixture formation process and, as a result, heat generation. An increase in the injection pressure leads to a decrease in emissions of soot and solid particles of hydrocarbons, more dispersed atomization of the fuel, which reduces the ignition delay time. The characteristics of heat generation and pressure in the cylinder become gentler, which allows increasing power, due to reduction of time for mixture formation. The angular intervals between the pilot and the main injection are determined by the optimal indicators of toxicity and noise of the diesel engine. The efficiency of using the battery system of high pressure fuel supply of Common Rail type to reduce emissions from exhaust gases increases with the use of the exhaust gas recirculation system.

Reference

[1] Shatrov M G, Golubkov L N, Dunin A U, Dushkin P V and Yakovenko A L 2017 The new generation of common rail fuel injection system for Russian locomotive diesel engines *Pollution Research* **36**(3) 678–84

[2] Shatrov M G, Sinyavski V V, Dunin A Y, Shishlov I G and Vakulenko A V 2017 Method of conversion of high- and middle-speed diesel engines into gas diesel engines *Facta Universit. Ser. Mechan. Engineer.* **15**(3) 383–95

[3] Shatrov M G, Golubkov L N, Dunin A U, Yakovenko A L and Dushkin P V 2015 Influence of high injection pressure on fuel injection performances and diesel engine working process *Thermal Sci.* **19**(6) 2245–53
[4] Shatrov M G, Golubkov L N, Dunin A U, Yakovenko A L and Dushkin P V 2015 Research of the injection pressure 2000 bar and more on diesel engine parameters Int. J. of Applied Res. 10(20) 41098–102

[5] Shatrov M G, Golubkov L N, Dunin A Yu, Dushkin P V and Yakovenko A L 2017 A method of control of injection rate shape by acting upon electromagnetic control valve of common rail injector Int. J. of Mech. Engineer. and Technol. 8(11) 676–90

[6] Shatrov M G, Sinyavski V V, Dunin A Yu, Shishlov I G, Vakulenko A V and Yakovenko A L 2018 Using simulation for development of the systems of automobile gas diesel engine and its operation control Int. J. of Engineer. and Technol. 7(2.28) 288–95

[7] Shatrov M G, Malchuk V I, Dunin A U and Yakovenko A L 2016 The influence of location of input edges of injection holes on hydraulic characteristics of injector the diesel fuel system Int. J. of Applied Engineer. Res., 11(20) 10267–73

[8] Shatrov M G, Malchuk V I, Dunin A Y, Shishlov I G and Sinyavski V V 2018 A control method of fuel distribution by combustion chamber zones and its dependence on injection conditions Thermal Sci. 22(5) 1425–34

[9] Shatrov M G, Golubkov L N, Dunin A U, Yakovenko A L and Dushkin P V 2016 Experimental research of hydrodynamic effects in common rail fuel system in case of multiple injection Int. J. of Applied Engineer. Res. 11(10) 6949–53

[10] Savastenko A A and Stepanova M E 2010 Features of the fuel equipment operation of a diesel engine with a two-stage system of fuel supply into the cylinder (Moscow: RUDN Publ) 107 p

[11] Savastenko A A, Kuzyakov V V, Devyanin S N and Starosvetsy V V 2003 Study of the staged fuel supply of fuel injection pump assembly of the company “Nippon Denso” (Moscow: RUDN) 74 p

[12] Savastenko, A A, Stepanova M E and Melnik I S 2010 Hydrodynamic processes in fuel equipment of a separated type with double-spring nozzles (Moscow: RUDN) 317 p

[13] Markov V A, Devyanin S N and Malchuk V I 2007 Injection and Atomization of Fuel in Diesel Engines (Moscow: BMSTU) 360 p

[14] Golubkov L N, Grishin A B and Emelyanov L A 2003 The results of calculation studies and optimization of the battery fuel system with electrically-controlled injectors Piston engines and fuels in the XXI century (Moscow: MADI) p 37