Improvement of Design of Diesel Injector Nozzles

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Abstract. The relevance of the article is explained by the necessity of improving fuel spraying and mixture formation processes in diesel engines. A design of injector nozzles enhancing the quality of the fuel injecting and spraying in diesel engines was proposed. The improvement of these processes is achieved by using a modified nozzle with different lengths of nozzle holes for injectors asymmetrically installed in diesel engines. Experimental studies of a D-245.12S diesel engine equipped with the injector nozzles serially produced and the modified injector nozzles were carried out. The possibility of improving the exhaust gas toxic characteristics of the diesel engine equipped with the modified injector nozzles was demonstrated. The installation of such nozzle in the diesel engine has allowed reducing the emission of nitrogen oxides by 2.1%, of carbon monoxide by 9.5%, and of unburned hydrocarbons by 10.9%, and reducing the average specific effective fuel consumption by 2.5 g/(kW•h), when the engine was operating in the 13-mode cycle ECE R49.

1. Introduction

Power and performance indicators of diesel engines and indicators of their exhaust gas toxicity are largely determined by the perfection of the fuel spraying and mixture formation processes. In its turn, the nature of the proceeding of these processes largely depends on the design of the fuel injection system. An essential element for a fuel injection system is the injector, which forms the characteristics of fuel injection and spraying. Injector design, and first of all, its nozzle, determines the geometrical features, structure, and fineness of fuel jets and many other parameters of fuel injection. Optimization of the rated parameters and characteristics in each operating mode is necessary for creating fuel supply equipment for transport diesel engines. The problem of the structural selection of fuel equipment elements is caused by a wide range of speed and load modes of the transport diesel and the used structures of the combustion chambers.

Many studies indicate that the mixture formation process is optimal if the mixture of oxygen with fuel is uniform in all zones [1, 2, 3]. This condition is ensured in case all the fuel jets reach the walls of the combustion chamber at the same time or with a little lag. It is usually assumed that all the nozzle holes have uniform diameter and length. However, it is not always possible to efficiently implement the mixture formation process, in particular, to ensure the necessary excess air coefficients in all regions of the combustion chamber in a wide range of engine operating conditions. Besides, it is essential to ensure the required spray fineness.
The quality of the mixture formation process is influenced by fuel properties, injection pressure, design of injector flow section, and primarily geometrical parameters of nozzle holes [3–6]. In this regard, numerous studies have been conducted on the effect of these parameters on the behaviors of fuel spraying and mixture formation processes [7–11]. In these studies, special attention was paid to the location and diameters of nozzle holes. The factors causing an increase in the flow turbulence in these holes and contributing to improving the quality of fuel spraying and mixture formation were evaluated [12–21]. The objective of this work is to experimentally assess the efficiency of adopting a nozzle design with different lengths of nozzle holes for injectors asymmetrically installed in diesel engines.

2. Materials and methods

2.1. Implementation of the Mixture Formation Process in Direct Injection Diesel Engines

It should be noted that the applied method of mixture formation predetermines the characteristics of the fuel combustion process and the selection of its design parameters: first of all, it is the selection of the combustion chamber type used in the diesel engine [3]. At present, various methods of fuel-air mixture formation (volumetric, film, and volume-film mixing) are used in direct injection diesel engines. Combustion chambers in a piston coupled with an asymmetrical (relative to the combustion chamber axis) injector arrangement are widely used in transport diesel engines. Such a constructive solution is implemented both in diesel engines of many foreign firms and in domestic diesel engines (Fig. 1) [3]. In some cases (for example, in diesel engines of MAN, Deutz, Continental), a displacement of the injector relative to the combustion chamber axis is determined by the features of the combustion process organization. But more often, the necessity to displace the injector relative to the axis of a combustion chamber inside piston is explained by the need to displace not only the injector in the cylinder head but also the valves of the gas distribution system. Such a design has been implemented, in particular, in domestic diesel engines D-240, D-245, YaMZ-238, and in many others [3].

![Figure 1. Schematic of combustion chambers in domestic diesel engines: a – D-21 (2C 10.5/12) and D-144 (4C 10.5/12); b – D-240 (4C 11/12.5); c – SMD-14N (4C 12/14); d – SMD-60 (6CN 13/11.5), SMD-62 (6CN 13/11.5), and SMD-31 (6CN 12/14); e – A-41 (4CN 13/14) and YaMZ-238 (8CN 13/14); f – D-108 (4C 14.5/20.5), D-160 (4CN 14.5/20.5), and D-200 (4CN 14.5/20.5); g – 8DVT-330 (8CN 15/16); h – V-30B (12CN 15/18); i – A-90TK (8CH 16.5/17).](image-url)
The fuel-air mixture formation process of the D-245.12S diesel engine (4 CN 11/12.5) produced by Minsk Motor Plant is characteristic. This type of diesel engine has a semi-separated combustion chamber of the CNIDI-type (Central Diesel Research Institute) and an asymmetrical arrangement of injectors. In this engine, the volume-film (wall) mixing with a part of fuel spray hitting the combustion chamber sidewalls adjacent to the neck is implemented, and injectors are installed in the cylinder head with an offset (Fig. 2). The fuel is injected into the hot edges of the neck and the combustion chamber’s inner walls near the neck, which ensures a stable ignition. One feature of this combustion chamber is that the neck diameter is approximately 30% of the piston diameter. As a result, a remarkable toroidal vortex movement of air is observed in the combustion chamber during the compression stroke, which ensures the required quality of mixing. The relatively large diameter of the combustion chamber neck contributes to the fact that hydraulic losses due to the overflow of air and the fuel-air mixture during the compression and expansion strokes are relatively small, and the fuel efficiency approaches that of diesel engines with unseparated combustion chambers.

![Figure 2](image)

**Figure 2.** The combustion chamber of the D-245.12S diesel engine with a schematic of injector displacement (a) and orientation of the fuel jets injected into the combustion chamber (b): 1, 2, 3, 4, 5 are the numbers of fuel jets injected.

The analysis of the studies of diesel engines with asymmetrical injector arrangement performed in work [3] proved the efficiency of improving the processes of fuel spraying and mixture formation by optimizing the values of the length of nozzle holes $l$. In the diesel engines with injector asymmetrically arranged relative to the combustion chamber axis, the distance between different nozzle holes and the combustion chamber walls is different. In this case, it is necessary to optimize the value of $l$ for each nozzle hole. Below we suggest such a method of improving the processes of fuel spraying and mixture formation in a diesel engine.

### 2.2. Improving the Design of Injector Nozzles

The FDM-22 injector is installed in the cylinder head with an offset of $\Delta l_i = 10$ mm relative to the central axis of the CNIDI combustion chamber in the D-245.12S diesel engine. This results in that different jets formed by the injector provide different mixing behavior. Jets 4 and 5 (see Figure 2.b) formed by nozzle holes most distant from the combustion chamber neck are characterized by their biggest length and realize mainly volumetric mixture formation. Jet 2, which has the shortest length, on the contrary, mainly performs film mixing. Therefore, comprehensive optimization of the flow part design of the injector is necessary for ensuring the best performance of the D-245.12S diesel engine.
Table 1. Parameters of the nozzle with a serial number 145.1112110 produced by NFEP.

| Diameter of nozzle holes \(d_s\), mm | Number of nozzle holes \(i_s\) | Maximum needle lift \(h_{nl}\), mm | Total efficient area of the nozzle assembly \(\mu_{fs}\), mm\(^2\) |
|--------------------------------|--------------------------------|---------------------------------|--------------------------------|
| 0.32                          | 5                              | 0.26                            | 0.278                          |

Note: \(\mu_{fs}\) values are given at maximum injector needle lift; the values of \(h_{nl}\) and \(\mu_{fs}\) are given as the average for a set of nozzles.

Table 2. The hole location of the nozzle with a serial number 145.1112110 produced by NFEP.

| Hole number | Angular location of the hole relative to the locating pin, degree | Angle of the hole relative to the nozzle axis, degree |
|-------------|---------------------------------------------------------------|----------------------------------------------------|
| 1           | 8                                                             | 62                                                |
| 2           | 90                                                            | 71.5                                              |
| 3           | 172                                                           | 62                                                |
| 4           | 237                                                           | 52                                                |
| 5           | 303                                                           | 52                                                |

Nozzles with a serial number 145.1112110 produced by Noginsk Fuel Equipment Plant (NFEP) are assembled with the FDM-22 injectors in the D-245.12S diesel engine, where the standard length of nozzle holes \(l_s\) is 0.90 mm with a diameter \(d_s\) of 0.32 mm and the ratio \(l_s/d_s = 2.81\). Some parameters of these nozzles are given in Table 1 and Table 2. The reduction of the fuel proportion hitting the combustion chamber walls, and, consequently, the increase of the proportion of the volumetric mixture formation in this diesel engine can be achieved by reducing the jet length of the fuel discharging from the nozzle holes closest to the combustion chamber walls. Therefore, it is advisable to form fuel jets with different lengths \(L\) to reduce the proportion of film mixture formation in the D-245.12S diesel engine. In this case, it is desirable to keep long fuel jets in the direction where the combustion chamber wall is far away from the nozzle hole tip, and short jets in the direction where the combustion chamber wall is close to the nozzle hole tip. Serial nozzles having five nozzle holes with a uniform geometrical dimension cannot provide different lengths of fuel jet during injecting. But the analysis of the data from work [3] shows that it is possible to reduce the length of some jets by decreasing the length \(l_s\) of the corresponding nozzle holes.

It was proposed to carry out additional modification of the tips of the NFEP nozzles in order to achieve different lengths of jets formed by nozzle holes with different lengths \(l_s\), according to the schematic in Fig. 3. It is implied that two nozzle holes farthest from the wall of the combustion chamber and forming jets 4 and 5 (see fig. 2.b) were left unchanged \((l_s = 0.90 \text{ mm}, d_s = 0.32 \text{ mm}, l_s/d_s = 2.81)\). The tip of the nozzle hole, which is nearest to the wall of the combustion chamber and forms jet 2, was polished to a length \(l_s = 0.45 \text{ mm} \,(l_s/d_s = 1.41)\). The tips of the nozzle hole forming jets 1 and 3 were polished to the length \(l_s = 0.70 \text{ mm} \,(l_s/d_s = 2.19)\).
Figure 3. Additional modification scheme for nozzle holes: 1, 3 – nozzle holes with a length of 0.70 mm; 2 – nozzle hole with a length of 0.45 mm; 4, 5 – nozzle holes with a length of 0.90 mm t is the standard (initial) length of nozzle holes.

2.3. Experimental setup and procedures

The evaluation of the efficiency of optimizing the $l/d$ ratio to improve the mixture formation process has been carried out in the term of the experimental studies of the aforementioned D-245.12S diesel engine, which is manufactured by Minsk Motor Plant and used for low-tonnage trucks ZIL-5301 Bychok. The tests of the diesel engine were conducted on a motor stand equipped with a set of necessary measuring equipment. The exhaust smokiness was measured using an MK-3 smoke meter by Hartridge (UK) with a measurement error of ±1%. The concentrations of nitrogen oxides NOx, carbon monoxide CO, and unburned hydrocarbons CHx in the exhaust gases were determined by a gas analyzer SAE-7532 by YANACO (Japan) with the measurement errors as to the indicated components of ±1%.

The diesel engine had a fuel system that includes a fuel injection pump assembly PP4M10U1f (Motorpal, Czech Republic) with a plunger diameter of $d_{pl} = 10$ mm and a total stroke of $h_{pl} = 10$ mm, high-pressure fuel lines of length $L_{FL} = 540$ mm and FDM-22 injectors. The initial injection pressure of the injectors has been adjusted to $p_{i,o} = 21.0$ MPa. The injectors were alternately equipped with the NFEP’s serial nozzles and the modified nozzles additionally modified according to the schematic in Fig. 3. The studies were performed in the full-load curve modes and 13-mode cycle of the UNECE Regulation 49 (ECE R49). During the tests, the installation advance angle of fuel injection equal to $\theta = 13^\circ$ crankshaft angle to the top dead center (TDC), and the position of the fuel supply rack remained unchanged at the maximum.

3. Results and Discussion

The results of the experimental tests of the D-245.12S diesel engine with the serial and modified nozzles in full-load curve modes and 13-mode cycle ECE R49 are shown in Fig. 4 and Fig. 5. The integral effective fuel consumption $g_{e, cond}$ and integral specific mass emissions of NOx, CO, and CHx ($e_{NOx}$, $e_{CO}$, $e_{CHx}$) have been calculated based on the experimental data obtained on the 13-mode test cycle in accordance with the generally accepted methods described in [3]. The results of these calculations are presented in Table 2.
Figure 4. The relation of the brake power $N_e$, torque $M_e$, total fuel consumption $G_F$, excess air coefficient $\alpha$, exhaust smoke $K_x$, and brake specific fuel consumption $g_e$ in the full-load curve modes with respect to the engine speed $n$ of the D-245.12S diesel engine with the use of the serial nozzles (1) or the modified nozzles (2).

Table 3. Indicators of the D-245.12S Diesel Engine with Different Types of Nozzles.

| Nozzle version | Conditional average fuel consumption for 13-cycle modes $g_{e,cond}$, g/(kW*h) | Integral specific mass emissions of toxic components on the 13-mode cycle, g/(kW*h) |
|----------------|---------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Serial nozzles | 272.6                                                                           | $e_{NOx}$ 5.749, $e_{CO}$ 7.872, $e_{CHx}$ 2.207                                |
| Modified nozzles | 270.1                                                                          | $e_{NOx}$ 5.631, $e_{CO}$ 7.126, $e_{CHx}$ 1.967                                |
Figure 5. The relations of the hourly fuel consumption $G_f$ (a), volumetric concentrations of nitric oxides $C_{NOx}$ in the exhaust gases (b), carbon monoxide $C_{CO}$ (c), and unburned hydrocarbons $C_{CHx}$ (d) with respect to the engine speed $n$ and torque $M_e$ of the D-245.12S diesel engine with the use of the serial nozzles (1) or the modified nozzles (2).

As shown in Fig. 4, the hourly fuel consumption that characterizes the average fuel mass flow rate through the injectors has been reduced after replacing the serial nozzles with the modified nozzles. This is because of the influence of nozzle hole geometry on the flow characteristics inside the nozzle hole. In the no-cavitation condition, a decrease in the length to diameter ratio of the nozzle hole leads to an increase in the fuel mass flow rate as a result of the reduced flow loss in the hole. However, in the cavitation condition, a decrease in the length to diameter ratio will cause an enhancement of cavitation inside the nozzle hole [22], which narrows the effective circulation cross-sectional area in the hole and eventually reduces the mass flow rate. The existence of cavitation in the investigated nozzle of the FDM-22 injector during the diesel engine operating at full loads has been confirmed in our previous studies [23, 24]. So the decreased discharge coefficient in the shortened nozzle holes means the drop in hourly fuel consumption, which in turn leads to a decrease in the brake power and torque of the diesel engine with the modified nozzles due to the reduced total energy carried by the fuel injected into the combustion chamber. A change in the length to diameter ratio of nozzle holes...
affects not only the internal flow in the nozzle but also the spray characteristics [25]. In the cavitation condition, a decrease in the length to diameter ratio is also accompanied by an increased injection velocity and an enhanced turbulence intensity at the nozzle outlet, which contributes to accelerating spray breakup, forming finer droplets, shortening the length of the liquid jet, and, increasing the spray angle. These facts enhance volumetric mixture formation and improve the mixture formation process. The improved spray process shortens the ignition delay, accelerates diffusion combustion, and enhances complete combustion. Eventually, after replacing the serial nozzles with the modified nozzles, the brake specific fuel consumption decreased, and the emission performance of the diesel engine was improved. As shown in Fig. 4, after adopting the modified nozzles, the brake specific fuel consumption $g_c$ decreased from 285.4 to 283.6 g/(kW·h) at the full load with the maximum engine speed $n = 2,400$ rpm and decreased from 248.9 to 243.9 g/(kW·h) on the maximum torque mode with $n = 1,500$ rpm, and following Table 3 the conditional average fuel consumption $g_{c\text{ cond}}$ for the diesel engine with the studied nozzles was reduced by 2.5 g/(kW·h). The reduction in the exhaust smoke and the emissions of toxic components was also confirmed. As shown in Fig. 4 and Fig. 5.d the exhaust smoke and the emission of CHx were reduced in all the tested modes. At the full load with the maximum engine speed $n = 2,400$ rpm, the exhaust smoke $K_e$ was reduced from 40 to 33% on the Hartridge scale (i.e. by 17.5%) and decreased from 49.5 to 48.0% (i.e. by 3%) on the maximum torque mode with $n = 1,500$ rpm. The integral specific mass emission of unburned hydrocarbons $e_{CHx}$ for 13-cycle modes was reduced from 2.207 to 1.967 g/(kW·h) (see Table 3), i.e. by 10.9%. A significant reduction of CO emission was observed under partial loads, and a little raise of NOx emission was only found on the maximum torque mode, as shown in Fig. 5.e after employing the modified nozzles. As presented in Table 3, the integral specific mass emissions of carbon monoxide emission $e_{CO}$ for 13-cycle modes decreased from 7.872 to 7.126 g/(kW·h), i.e. by 9.5%. The obvious reduction of NOx emission was noted at the full load with the maximum engine speed of $n = 2,400$ rpm, where the concentration of NOx in the exhaust gases decreased from 445 ppm to 421 ppm. According to Table 3, the integral specific mass emission of nitrogen oxides $e_{NOx}$ for 13-cycle modes was reduced from 5.749 to 5.631 g/(kW·h), i.e. by 2.1%.

4. Conclusion

The method for improving the processes of fuel spraying and mixture formation is proposed. It is to change the length of each of the nozzle holes, depending on the displacement of the injector relative to the combustion chamber axis. The experimental studies conducted on the D-245.12S diesel engine confirmed the efficiency of the use of nozzles with different lengths of nozzle holes.

After employing the nozzles modified based on the serial nozzles, the fuel efficiency and the emission performance of the diesel engine were improved.

(1) The brake specific fuel consumption $g_c$ was noticeably lower in the full-load curve modes when the modified nozzles were used. At the full load with the maximum engine speed, the brake specific fuel consumption $g_c$ decreased from 285.4 to 283.6 g/(kW·h), and on the maximum torque mode, the decreased 248.9 to 243.9 g/(kW·h). The conditional average fuel consumption $g_{c\text{ cond}}$ in the 13-mode cycle was reduced by 2.5 g/(kW·h).

(2) The exhaust smoke significantly decreased by employing the modified nozzles. At the full load with the maximum engine speed and on the maximum torque mode, the relative reduction in the exhaust smoke scale was 17.5% and 3.0%, respectively.

(3) The use of the modified nozzles has a favorable effect on exhaust gas toxicity. The integral specific mass emission of nitrogen oxides $e_{NOx}$ was reduced from 5.749 to 5.631 g/(kW·h), i.e. by 2.1%. At the same time, the integral specific mass emission of carbon monoxide $e_{CO}$ decreased from 7.872 to 7.126 g/(kW·h), i.e. by 9.5%, and the integral specific mass emission of unburned hydrocarbons $e_{CHx}$ was reduced from 2.207 to 1.967 g/(kW·h), i.e. by 10.9%.
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