Development of the integrated IKTS-MADI complex for design and research of common rail fuel systems of diesel engines with electronic control

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Abstract. Further tightening of environmental rules and standards regulating the content of toxic substances in diesel exhaust gases, accompanied by an increase in the requirements for their fuel efficiency, creates prerequisites for the creation of Russian common rail fuel systems (CR). The performance of this task is possible with the use of new engineering solutions in combination with computational and experimental research methods implemented on the basis of the integrated computational and experimental complex IKTS-MADI. The complex consists of computing and research components. The computing component of the IKTS-MADI allows calculating the working processes of the entire high-pressure line when the high-pressure fuel pump (HPFP), rail and electro-hydraulic common rail injectors (CRI) work together, taking into account the influence of wave phenomena on the distribution of injection parameters across diesel cylinders. Obtaining new data to expand the library of existing technical solutions and testing of fuel equipment samples designed using mathematical modeling are carried out on the research component of IKTS-MADI. The CR and its components are tested together with the control system (control unit, sensors and wiring harnesses). The injection characteristics required for calculating the diesel operating process are recorded.

1. Introduction

The further tightening of ecological standards specifying the content of toxic emissions in the exhaust gases of diesel engines [1], jointly with the need to improve fuel efficiency and use alternative fuels [2], creates prerequisites for perfection of the CR fuel systems of diesel engines. The fields of this perfection are:

- raising injection pressure up to 300 MPa [3, 4, 5];
- control of fuel distribution by the combustion chamber zones [6];
- ensuring the required shape of the front edge of the injection rate [7].

The desired fuel injection law at any operation mode of the engine is formed by variation of the control impulse duration and pressure in the common rail. It also depends on wave phenomenon originating in the high-pressure line and having a considerable impact on the fuel injection process in case of a multistage injection [8, 9].

These problems can be solved using the developed integrated computational and experimental complex IKTS-MADI.
2. Description of the developed integrated computational and experimental complex IKTS-MADI

To develop the design of the CR and fine-tune its working process, an integrated calculation and experimental complex IKTS-MADI was created for cooperative research and adaptation of the working processes of diesels and their fuel systems. The complex consists of computing and research components.

The IKTS-MADI structure allows implementing the following strategies for research and adaptation of working processes of diesels and its fuel systems:

- exploratory research – after conducting initial experimental studies, additions are made to the mathematical models of the working processes of diesel and its fuel system. Then a search for a new technical solution is carried out, taking into account the specified restrictions;
- selection of a possible technical solution for the fuel system from those proposed by conducting a computational research, its experimental verification on a non-engine stand, and evaluation of the efficiency of it using to improve the performance of the diesel working process;
- parallel design of the fuel system with the diesel control system and debugging of their cooperative operation.

The computational component of IKTS-MADI consists of:

- non-engine stand B01.00.00.000 (figure 1) with tools for testing elements of direct-acting and common rail fuel systems elements;
- engine stand with single-cylinder engine M01.00.000 on the basis of a universal crankcase for studying the cooperative operation of diesel with experimental samples of fuel equipment with electronic control;
- non-engine stand PLTD. 387442.70.00 and measuring equipment (figure 2) for experimental research and testing of a full-size set of fuel systems with a diesel control system (figure 3).

The distinctive features of the research component: testing fuel system with pressure of 300 MPa; determine the power required to drive the fuel pump (up to 87 kW); a control system for the fuel system including the electronic unit with the necessary algorithms and sensors required to control the transport diesel.

To create a simulation of the operation of the electronic control system as part of the engine, disks (figure 3) of sensors position for the crankshaft 1 and camshafts 3 are installed on the test stand, similar to those installed on electronically controlled diesels.

**Figure 1.** Non-engine stand B01.00.00.000 for testing elements of direct-acting and common rail fuel supply systems:

1 – electric motor; 2 – high-pressure fuel pump; 3 – oscilloscope; 4 – electrohydraulic injector; 5 – speed controller; 6 – bed; 7 – chamber for recording injection characteristics; 8 – rail.

When the test stand is running, the disks rotates, simulating the rotation of the engine crankshaft, and the control unit receives signals from the crankshaft position sensor located above the disk 4 having 60-2 teeth, which determines the engine speed, and from the camshaft position sensor located above the disk 2 having 6+1 tooth, which synchronizes the control pulses on the injectors relative to the conditional position of the top dead point of the first cylinder of the engine.
A mockup of the pressure control unit was created for conducting research. The development and production of the pressure control unit mockup was carried out in several stages.

- development of the PI-controller algorithm.
- development of the pressure control unit mockup.
- development of software and its transfer in the microcontroller of the control unit pressure.
- "on the table" debugging the developed system and determining of the pressure sensor characteristics.
- calibration of the integral and proportional parts coefficients of the controller on the test stand.

Figure 2. Non-engine stand PLTD.387442.70.00 and measuring equipment:
1 – measuring stand; 2 – registering parts of fuel flow meters; 3 – measuring parts of flow meters; 4 – fuel filter; 5 – oscilloscope for registering the control signal coming to the injector electromagnet; 6 – bed for mounting a high-pressure fuel pump; 7 – oscilloscope for registering changes in fuel pressure in the high-pressure line; 8 – measuring cup; 9 – stand for the injector mounting; 10 – electro-hydraulic injectors; 11 – hose for removing fuel spent on injector control; 12 – support for injectors mounting; 13 – fuel pipes.
Figure 3. Placement of diesel control system elements on the non-motor stand PLTD.387442.70.00:
1 – crankshaft position sensor; 2 – 6+1 disc; 3 – camshaft position sensor; 4 – 60-2 disc; 5 – control unit; 6 – electric brake machine.

Determination of the hydraulic characteristics of the CRI spray holes is carried out at a stationary fuel flow on the experimental stand shown in figure 4. At the same time, the pressure at the inlet of the nozzle reaches 150 MPa, and in the working chamber – 16 MPa, which corresponds to the conditions of injection into the combustion chamber of a modern diesel engine.

Figure 4. Structural diagram of an experimental stand for recording the hydraulic characteristics of nozzles:
1 – electric motor of the low-pressure fuel pump drive; 2 – electric motor of the high-pressure fuel pump drive; 3 – low-pressure fuel pump; 4 – high-pressure fuel pump; 5 – filter unit for fine fuel purification; 6 – arrow gauges; 7 – high–capacity rail; 8 – small rail; 9 – valve for adjusting the volume of fuel being passed; 10 – throttling valve for fine adjustment of the injection pressure; 11 – injector body with a nozzle and needle lift indicator; 12 – chamber; 13 – valve for adjusting the back pressure in spillage chamber; 14 – choke with electric actuator; 15 – measuring vessel; 16 – fuel tank; 17 – heat exchanger for fuel cooling.
Using complex, it is possible to carry out a full cycle of work related to testing and modification of fuel systems:

- checking the efficiency and effectiveness of the selected technical solutions of individual elements of the fuel system (element-by-element tests): high-pressure fuel pump, CRI, rail, high-pressure fuel lines, low-pressure lines;
- determining the characteristics of fuel system elements (hydraulic, speed, load and pressure characteristics);
- estimation of the power required to drive the fuel pump;
- full-size fuel system tests;
- debugging the cooperative operation of the control system and the test sample of the fuel system;
- study of the operation of the fuel system as part of a diesel engine with a primary assessment of its power, environmental and economic indicators;
- initial calibration of the diesel control system.

The calculation component of IKTS-MADI includes mathematical models and software packages based on them:

- hydrodynamic calculation of processes occurring in fuel systems;
- the diesel working process.

Working with the calculation complex provides a choice between modeling existing technical solutions and building a model focused on a new design, after making the necessary changes, obtained on the processing the results of experimental studies conducted using the research component (figures 1, 2 and 4).

The entire high-pressure line of the CR is represented by pipelines and cavities with control elements (valves, jets, etc.).

Figure 5 shows the main layout diagrams of the high-pressure line of the CR, which are presented in the IKTS-MADI complex as basic technical solutions: a fuel pump with a single CRI; a CRFS with a serial CRI connection; a CR with a parallel CRI connection.

The calculation of the fuel pump with one EHI is basic (figure 5, a). The design diagram of the high-pressure line (HPL) for this variant is shown in figure 6.

For figure 6: $F_1(t)$ and $W_1(t)$ – direct and reverse wave in the high pressure line in fuel pump rail; $p_{акк}$ – pressure in the main rail; $\rho_0$ is the density of fuel in the main rail; $F_1(t+\Delta t)$ and $W_1(t+\Delta t)$ – direct and reverse wave in the high pressure line in the CRI rail; $p_{акк CRI}$ – pressure in the CRI rail; $\rho_{акк CRI}$ – fuel density in CRI rail; $F_2(t)$ and $W_2(t)$ – direct and reverse wave in the channel from a CRI rail to the internal volume in the CRI body.

To calculate the effect of wave processes in a CR with a sequential connection of injectors (figure 5, b), the mathematical model of HPL with a single CRI was supplemented with the necessary algorithms that determine the nature of the connection of nodes and the formation of wave processes.

The fuel system was divided into six nodes. Each node consisted of an CRI and a fuel line connected to it (such a fuel line is the one whose opposite end is located closer to the main rail). Thus, three types of nodes were formed:

- the first type of node consists of an CRI, a connected fuel line that is joined to the main rail, and a fuel line that goes to the next CRI;
- the second type of node (4 pcs.) it consists of an CRI, a connected fuel line that is joined to the rail of the previous CRI, and a fuel line that goes to the next CRI;
- the third node consists of an CRI and a connected fuel line that is joined to the battery of the previous CRI.

The calculation scheme for the last (sixth) CRI has not changed, since it completely repeats the variant with a single CRI (figure 6).
The scheme for CRI from the first to the fifth takes into account the movement of forward and reverse waves in the high-pressure fuel line at the rail of the current injector moving to/from the next CRI.

In accordance with the scheme, the mass balance equation for the CRI rail, expressed in terms of density change, for a single CRI (1) is modified for CRI from 1 to 5 with two supply pipelines (2)

\[
\rho_{acc\text{ CRI} n}^i = \rho_{acc\text{ CRI} n}^{i-1} + \frac{\Delta \tau}{6 \cdot n_e \cdot V_{acc\text{ CRI}}} \left( f_{m1} \cdot \rho_{acc\text{ CRI} n}^{i-1} \right) \left( \frac{F_{1n}(m) \cdot e^{-\frac{k_1 \cdot L_1}{a}}}{a} - W_{n}(m) \right) - \\
- \left( \frac{f_{m2} \cdot \rho_{acc\text{ CRI} n}^{i-1}}{a \cdot \rho_0} \right) \left( F_{2n}(0) - W_{2n}(0) \cdot e^{-\frac{k_2 \cdot L_2}{a}} \right)
\]

where: \( \rho_{acc\text{ CRI} n}^i \) – the current fuel density in the rail of the n-th CRI; \( \rho_{acc\text{ CRI} n}^{i-1} \) – fuel density in the rail of the n-th CRI at the previous integration step; \( \Delta \tau \) – integration step; \( n_e \) – engine shaft speed; \( V_{acc\text{ CRI}} \) – volume of the CRI battery; \( f_{m1}, f_{m2} \) – cross-section area of the connected fuel line and channel to the volume in the CRI body; \( a \) – speed of sound in the fuel; \( \rho_0 \) – fuel density under initial conditions; \( F_{1n}(0), W_{1n}(0), F_{1n}(m), W_{1n}(m) \) – forward and reverse waves at the beginning and end of the pipeline connected to CRI; \( F_{2n}(0), W_{2n}(0), F_{2n}(m), W_{2n}(m) \) – forward and reverse wave at the beginning and end of the channel from the CRI rail to the volume in the internal CRI cavity.

\[
\rho_{acc\text{ CRI} n}^i = \rho_{acc\text{ CRI} n}^{i-1} + \frac{\Delta \tau}{6 \cdot n_e \cdot V_{acc\text{ CRI}}} \left( f_{m1} \cdot \rho_{acc\text{ CRI} n}^{i-1} \right) \left( F_{1n}(m) \cdot e^{-\frac{k_1 \cdot L_1}{a}} - W_{n}(m) \right) - \\
- \left( \frac{f_{m2} \cdot \rho_{acc\text{ CRI} n}^{i-1}}{a \cdot \rho_0} \right) \left( F_{2n}(0) - W_{2n}(0) \cdot e^{-\frac{k_2 \cdot L_2}{a}} \right) - \\
- \left( \frac{f_{m1} \cdot \rho_{acc\text{ CRI} n}^{i-1}}{a \cdot \rho_0} \right) \left( F_{1n+1}(0) - W_{n+1}(0) \cdot e^{-\frac{k_1 \cdot L_{n+1}}{a}} \right)
\]

where \( F_{1n+1}(0), W_{n+1}(0) \) – forward and reverse waves at the beginning of the pipeline going from CRI \( n \) to \( n+1 \).

When the CRI is connected in parallel (figure 5, b), two local rails are added to the HPL design scheme, to which three CRI with fuel lines are connected and two fuel lines. The first of it connect the main and first local rails, and the second connect the local rails to each other.
Figure 5. Layout diagrams of the CR high-pressure line used in the design component of the IKTS-MADI complex:

a – fuel pump with one CRI; b – serial connection of CRI; c – parallel connection of CRI;
1 – high-pressure fuel pump; 2 – electro-hydraulic injector; 3, 4-high-pressure fuel lines; 5 – rail.
Figure 6. Calculation scheme of a high-pressure line with one CRI:
1 – rail; 2 – high-pressure fuel line; 3 – CRI rail.

The calculation scheme of the first rail is shown in figure 7.

Figure 7. Calculation scheme of the first local rail with parallel CRI connection.

For figure 7: $F_{01}(t+\Delta t)$ $\&$ $W_{01}(t+\Delta t)$ – forward and reverse waves in the high-pressure fuel line (main rail–local rail) for the first local rail; $\rho_{loc\ acc\ 1}$ – pressure in the first local rail; $F_{12}(t)$ $\&$ $W_{12}(t)$ (not shown), $F_{13}(t)$, $W_{13}(t)$ – forward and reverse waves in the fuel line connecting the first local rail and the CRI rail from Nos. 1 to 3.

Based on the presented scheme (figure 7), the equation for the fuel density changing in the rail has the form:

$$
\rho_{loc\ acc\ 1} = \rho_{loc\ acc\ 1}^{i-1} + \frac{\Delta \tau}{6 \cdot n_{e} \cdot V_{loc\ acc}} \left( \frac{f_{m0} \cdot \rho_{loc\ acc\ 1}^{i-1}}{a \cdot \rho_{0}} \right) \left( F_{01}(m) \cdot e^{-\frac{k_{0} \cdot L_{01}}{a}} - W_{01}(m) \right) -
\left( \frac{f_{m0} \cdot \rho_{loc\ acc\ 1}^{i-1}}{a \cdot \rho_{0}} \right) \left( F_{02}(0) - W_{02}(0) \cdot e^{-\frac{k_{0} \cdot L_{02}}{a}} \right) -
\left( \frac{f_{m1} \cdot \rho_{loc\ acc\ 1}^{i-1}}{a \cdot \rho_{0}} \right) \left( F_{11}(0) - W_{11}(0) \cdot e^{-\frac{k_{1} \cdot L_{11}}{a}} \right) -
\left( \frac{f_{m2} \cdot \rho_{loc\ acc\ 1}^{i-1}}{a \cdot \rho_{0}} \right) \left( F_{12}(0) - W_{12}(0) \cdot e^{-\frac{k_{1} \cdot L_{12}}{a}} \right) -
\left( \frac{f_{m3} \cdot \rho_{loc\ acc\ 1}^{i-1}}{a \cdot \rho_{0}} \right) \left( F_{13}(0) - W_{13}(0) \cdot e^{-\frac{k_{1} \cdot L_{13}}{a}} \right)
$$

(3)

For the second local rail, the calculation scheme is shown in figure 8.
For figure 8: $F_{02}(t+\Delta t)$ и $W_{02}(t+\Delta t)$ – forward and reverse waves in the high-pressure fuel line (second local rail – first local rail); $\rho_{loc acc 2}$ – pressure in the second local rail; $F_{14}(t)$, $W_{14}(t)$, $F_{15}(t)$ (not shown), $W_{15}(t)$ (not shown), $F_{16}(t)$, $W_{16}(t)$ – direct and reverse wave in the fuel line connecting the second local rail and the CRI rail from Nos 4 to 6.

The equation for the fuel density changing has the form:

$$\rho_{loc acc 2}^i = \rho_{loc acc 2}^{i-1} + \frac{\Delta \tau}{6 \cdot n_e \cdot V_{loc acc}} \left[ \left( \frac{m1 \cdot \rho_{loc acc 2}^{i-1}}{a \cdot \rho_0} \right) F_{02}(m) \cdot e^{-\frac{k_0 L_{a2}}{a}} - W_{02}(m) \right] - \left( \frac{m4 \cdot \rho_{loc acc 2}^{i-1}}{a \cdot \rho_0} \right) F_{14}(0) - W_{14}(0) \cdot e^{-\frac{k_1 L_{a4}}{a}} - \left( \frac{m5 \cdot \rho_{loc acc 2}^{i-1}}{a \cdot \rho_0} \right) F_{15}(0) - W_{15}(0) \cdot e^{-\frac{k_1 L_{a5}}{a}}$$

(4)

3. Conclusions
1. An integrated computational and experimental complex IKTS-MADI has been created. The structure of the complex allows to choose a possible technical solution for the fuel system, its experimental verification and evaluation of the it using efficiency to improve the performance of the diesel working process.

2. A method for calculating the high-pressure line of the common rail fuel system has been developed. The basic technical solutions in the IKTS-MADI complex are: fuel pump with one CRI; CR with a serial CRI connection; CR with a parallel CRI connection.

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