Fuel flow and pressure in common return line as a diagnostic parameter of electro-hydraulic injectors technical state

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Abstract. Electro-hydraulic injectors (EHI) are the most vulnerable components of the common rail injection system of a modern diesel engine. As a rule, the injectors' diagnostics begins with the analysis of data of the automobile scanner. These data include the current of the high-pressure pump metering device, adjustment of fuel pulsewidth when balancing the engine cylinders. A comprehensive analysis carried out by means of a car scanner can be possible only if a pressure sensor is positioned in the control chamber of the injector of the common rail injection system. There are such systems, however the majority of cars, not equipped with them. The scanner data may be influenced by the technical state both of the engine and of the metering device. Consequently, it can be impossible to assess the technical state of the injectors only by means of the car scanner data. It is known that the technical state of the common rail injector is characterized by such indicator as individual fuel back drain. There is a method of measuring the injectors' individual leakages by back flow measuring, but it can be applied only if there is an access to individual drain nozzles of EHI. In many existing common rail injection systems the injectors are located inside the engine, the access to them is hindered. Respectively, only the common return line access is available. High-quality diagnostics of injectors in such systems is possible only with the use of specialized testers, which inevitably leads to increased costs conditioned by disassembling and fitting. To reduce the time of diagnosing electro-hydraulic injectors significantly, a method of determining their individual backflow by the common return line was developed.

1. Introduction
Due to their advantages common rail injection systems are widely used in the world automobile production [1,2]. However, the efficiency of the vehicle operation depends on its unplanned dead time caused by different malfunctions. That is why one of the important tasks is to reduce the time of technical manipulations with a car, when assessing its technical state and performing the fault diagnostics.

The main part of common rail injection systems failures is represented by electro-hydraulic injectors malfunctioning [3]. In most cases the proper functioning of an injector is guaranteed by leak tightness of the control chamber, which valve plays a key role in this process [4]. The valve of the control chamber has a sufficiently small contact area of the working surface in relation to other moving parts of the injector and it is under high intensity loads. If the fuel is contaminated, it becomes the most vulnerable item in the chain of electro-hydraulic injector parts.

A leaky valve causes a pressure decrease in the control chamber, which violates the dynamics both of the plunger-multiplier movements and of the needle valve of the nozzle. The amount of fuel injected begins to increase. The result of the given process is not only a failure of the common rail injector itself,
but a complete engine failure as well. Thus, it is relevant to develop operating methods of monitoring the EHI technical state [5,6].

The method of diagnostics by the common return line allows monitoring the technical state of electro-hydraulic injectors while in operation as well as predicting their future functioning.

2. Theoretical Background
An electro-hydraulic injector is a complex precision mechanism [7]. The relations between the injector parts depend on its internal parameters (Figure 1). During the operating time, structural parameters, as a rule, change. Structural changes include defects of the locking edge of the control chamber valve, they form the flow area when the valve is closed [8].

![Diagram of Electro-Hydraulic Injector Functioning.](image)

Parameters determining the functioning modes: \( \rho_f \) – fuel density; \( \nu_f \) – fuel viscosity; \( p_r \) – common rail fuel pressure; \( t_r \) – common rail fuel temperature.

External impact parameter: \( t_a \) – ambient temperature.

Output parameters: \( q \) – fuel delivery; \( Q \) – fuel drain; \( Q_{pl} \) – fuel flow through the plunger seal; \( Q_n \) – fuel flow through the piston part of the needle valve; \( p_d \) – pressure in the return line.

Structural parameters: \( \mu f_1 \) – flow area of the filling orifice; \( \mu f_2 \) – flow area of the drain orifice; \( \mu f_3 \) – flow area at the edge of the closed control chamber valve; \( \delta_{pl} \) – clearance space between the plunger bushing and multiplier; \( \delta_n \) – clearance space between the needle and its guide bushing.

Adjustment parameters: \( h_a \) – armature stroke; \( \delta_m \) – magnetic gap; \( s_v \) – force of the control chamber spring; \( x_v \) – control chamber valve stroke; \( s_n \) – force of the needle valve spring; \( x_n \) – needle valve stroke.

Internal control parameters: \( p_v \) – pressure in the control chamber; \( F(p_v) \) – force applied to the plunger-multiplier; \( F(p_{inj}) \) – force applied to the needle valve.
Fluid motion is based on Navier-Stokes differential equations for the case of non-permanent one-dimensional fuel motion and the flow continuity equation. Coriolis and gravitational forces are not taken into account. The bulk modulus factor and the sound speed are not used in solving these equations directly. However, they can be calculated as follows.

The sound speed is calculated as:

\[ c = \left( \gamma \left( \frac{\partial p}{\partial \rho} \right) \right)^{-\frac{1}{2}} \]  

where \( \gamma \) – specific heats ratio.

As density is a true function of pressure and temperature, the property of derivatives can be used to convert \( \frac{dP}{dT} \) into density derivatives on pressure and temperature basis. Finally, the formula is transformed to get the expression for \( \gamma \):

\[ \gamma = \left( 1 - \frac{T \left( \frac{\partial p}{\partial T} \right)_p^2}{C_p \rho^2 \left( \frac{\partial \rho}{\partial T} \right)_p} \right)^{-1} \]  

The isothermal (or adiabatic) bulk modulus is determined as:

\[ \beta_{ad} = \rho \gamma \left( \frac{\partial \rho}{\partial p} \right)_p^{-1} = \gamma \beta_i \]  

where \( \beta_i \) – isothermal bulk modulus.

In the first place the process of development of pressure and consumption required for control in the return line must be described by the equation of pressure change in the control chamber (Fig. 1). At the same time, other leakages caused by the valve wear are modelled as fuel flow \( Q_3 \). In this case the well-known volume balance equation for the injector control chamber can be used:

\[ \frac{dP}{dt} = \left( Q_1 - Q_2 - Q_3 - \frac{\pi d_p^2}{4} \cdot \frac{dz}{dt} \right) \left( \beta \left( V_i - z \cdot \frac{\pi d_p^2}{4} \right) \right)^{-1} \]  

where \( Q_1 \) – fuel flow through the jet filling bore; \( Q_2 \) – fuel flow through the jet drain bore; \( Q_3 \) – fuel flow through another jet bore between the control chamber and the volume between the valve and the drain jet bore (fuel leakages caused by wear); \( d_p \) – diameter of the plunger-multiplier; \( V_i \) – initial volume of the control chamber; \( z \) – displacement of the plunger-multiplier; \( \beta \) – (bulk modulus).

The first order approximation is applied to the density change depending on pressure and temperature. This model is useful if the bulk modulus and the thermal expansion factor are known at one point or at several points [9, 10].

The fuel flow through the flow area \( i \) is:

\[ Q_i = c_i \cdot A_i \left( \frac{2}{\rho} \cdot P \right)^\frac{1}{2} \]  

where \( c_i \) – discharge coefficient of area \( i \); \( A_i \) – cross sectional area of \( i \); \( \Delta P \) – pressure difference between inlet and outlet.

Discharge coefficients through the orifices were determined experimentally on the basis of GT-Suite taking into account the modes of flow and vapor separation phenomenon.

The equation mentioned above can be rearranged for \( c_0 \) determining on the basis of the given experimental differential pressure and flow through the valve:
where \( Q \) – volume flow rate; \( D_{\text{up}} \) – diameter before the throttle or the valve; \( \Delta P_{\text{st}} \) – static pressure decrease when passing through the throttle or the valve; \( D \) – reference diameter of the throttle or the valve; \( \rho \) – fluid density.

The equations of moving parts as well as of electrodynamic processes are widely known and described in various scientific works e.g. [5, 8-11]; they are not given in this article.

On the one hand, the fuel flow through the control chamber valve seal \( Q_i \) increases the leakage, on the other hand, it reduces the pressure in the control chamber of EHI. Consequently, the pressure developing in the return line with each EHI actuation depends on the pressure in the injector control chamber, that is, on its technical state.

The method of determining individual leakages by pressure and fuel flow in the return line involves determining the proportion of each EHI in the measured total flow rate by means of the pressure analysis in the common return line.

Processing the experimental data shows that the numerical integral of the pressure graph section reflecting the corresponding injector about the axis of the average pressure of all the sections is an informative testing parameter:

\[
P_i = \int_{t_i}^{t_{i+1}} P_i dt ,
\]

where \( P_i \) – numerical integral value on the section; \( P_n \) – value of pressure of one integration step.

\[
P = \sum_i P_i \cdot n_i^{-1},
\]

where \( P \) – average value of the pressure graph section; \( n_i \) – the number of section points.

There is an inverse relation between the pressure developed due to EHI actuation on the section \( P_i \) and the average pressure \( P \) in the return line that is why the individual back flow is calculated as follows:

\[
Q_i = Q \cdot P_i^{-1} \left( \sum_i P_i^{-1} \right)^{-1},
\]

where \( Q \) – measured total fuel back flow.

### 3. Methods and Materials

Experimental research was conducted on a GAZelle-Business car. When planning this experiment, the required number of tests, their methods and modes were determined in order to obtain the necessary quantity and quality of experimental data. The experiment included the following steps:

1. Equipment preparation: installation of EHI shaving the nominal technical state; preparation and standardization of one EHI with the peak technical state; connecting and checking the hydraulic and electrical connections of the diagnostic device; checking the performance of the connected equipment, test run.

2. Warm-up of the engine up to the operating temperature of 80º C.

3. Measurement of individual and total fuel consumption required for EHI control using measuring containers. Comparing the received values with the parameters of consumption needed for the control of EHI with the nominal technical condition. The initial technical state of the EHI is nominal.

4. Measuring and recording of the received data on fuel flow and pressure in the common return line with the use of the device.

5. Replacement of the EHI with the nominal technical state by the prepared EHI with the marginal technical state in the first cylinder.

6. Measurement of individual and total fuel consumption required for EHI control using measuring containers. Comparing the received flow rate values required for the control of the cyclic fuel pulses with the parameters of Items 3 and 5.
7. Measuring and recording of the received data on fuel flow and pressure in the common return line using the device.
8. Rollback of the EHI structure of the engine.
9. Repeating the operations for the second, third and fourth cylinders according to Items 5, 7 and 8.

Figure 2. Experiment Conducted with a GAZelle-Business Car.

Figure 3. Diagram of Connection of the Device for EHI Diagnostics by Common Return Line of the Engine, the Russian Federation Patent No. 267299: 1 – measuring unit; 2 – connection to the common return line; 3 – common return line; 4 – inlet pipe; 5 – drain pipe; 6 – cables of supplementary devices; 7 – clock pulse sensor; 8 – high pressure control; 9 – PC; 10 – USB connection; 11 – fuel tank; 12 – supply line; 13 – fuel filter; 14 – high-pressure fuel pump; 15 – fuel pressure accumulator; 16 – pressure-relief valve; 17 – injector; 18 – engine control unit; 19 – wiring; 20 – connector; 21 – engine; 22 – crankshaft; 23 – high-pressure line.

The experimental research was conducted on a GAZelle-Business car with the ISF 2.8 Cummins engine. To do this, a device was developed that allows measuring pressure and fuel flow in the common
return line of the vehicle (Fig. 2). The method and device for diagnosing fuel flow and pressure in the common return line are protected by the patent of the Russian Federation No. 267299 [12] (Figure 3).

4. Results and discussion
The graph of pressure in the EHI control chamber was obtained via mathematical modelling by means of the specialized software GT-SUITE.

The injector with the marginal technical state positioned in the second cylinder caused reduced pressure in the control chamber. It is expressed by the pressure peak decrease at the main injection (Figure 4).

![Figure 4. Pressure in EHI Control Chamber (calculation).](image)

The experiment showed that the pressure in the common return line relevant for the injector with the marginal technical state also decreased as compared with the injectors with the nominal technical state (Figure 5, 6).

![Figure 5. Graph of all the EHIs with Nominal Technical State, Idle Mode.](image)
Figure 6. Graph of EHI with Marginal Technical State in the 3rd Cylinder, Idle Mode.

The numerical integration of the graph sections of each EHI is shown in Figure 7. The dark areas indicate the desired areas limited by the pressure graph about the abscissa axis formed by the average pressure value of the 1st, 2nd, 3rd and 4th cylinder sections.

Figure 7. Desired Areas Limited by Pressure Graph where 1, 2, 3 and 4 – Numbers of EHI of Corresponding Cylinders, Idle Mode.

Mathematical processing of the experimental data allowed receiving the following data (Table 1). It presents two cases: when all the electro-hydraulic injectors are of nominal technical state in terms of fuel backflow; when one of the injectors was defined as a marginal one by the bench control (installed on the third cylinder).

| Table 1. Calculation of Fuel Backflow Balance of the Common Return Line. |
|-------------------------------------------------|
| Balance | Back Flow | Balance | Back Flow | Balance | Back Flow | Balance | Back Flow |
| injector | injector 1 | injector 3 | injector 3 | injector 4 | injector 4 | injector 2 | injector 2 |
| %       | ml/min    | %       | ml/min    | %       | ml/min    | %       | ml/min    |
| All injectors are nominal | 19.6 | 7.5 | 28.5 | 10.9 | 29.8 | 11.4 | 22.1 | 8.4 |
| Damaged injector in Cylinder 1 | 35.2 | 21.5 | 21.7 | 13.3 | 18.8 | 11.5 | 24.3 | 14.9 |
5. Findings
In the course of the research, the relationship between individual fuel back flow required for EHI control and the numerical integral indicators of the relevant sections of the fuel pressure graph in the common return line was determined. It is desirable to use numerical integral indicators for processing the pressure graph. Experimental data allow determining the injector with the marginal technical state by fuel flow and pressure in the common return line with the accuracy that is sufficient for practical use. To increase the accuracy, reliability and self-descriptiveness of the proposed method, additional research must be carried out.

6. Conclusion
The method of electro-hydraulic injectors diagnostics by fuel flow and pressure in the common return line allows for significant reduction in time and labor intensity as compared to the similar diagnostic procedures performed according to the existing methods.

The proposed method can also be a helpful complement to the diagnostic methods of common rail injection systems that are already known and widely used.

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