Modelling the High-speed Injector for Diesel ICE

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Abstract. The article describes the results of research on the option of improving the operation speed of the electro-hydraulically driven injectors (Common Rail) for diesel ICE. The injector investigated in this article is a modified serial injector Common Rail-type with solenoid. The model and the injector parameters are represented in the package LMS Imagine.Lab AMESim with the detailed description of the substantiation and background for the research. Following the research results, the advantages of the proposed approach to analysing the operation speed were detected with outlining the direction of future studies.

1. Introduction

In the fuel injection systems of diesel internal combustion engines (ICE), there is a problem of overcoming the contradiction between the fuel injection laws and ensuring the fuel atomization quality. The characteristics of injection and spraying of fuel depends on the design of the nozzle. The characteristics such as: the geometric characteristics of flow of sprayed fuel, the structure of the fuel flare, the fineness of fuel spraying, a number of other parameters of the fuel supply process. To ensure high-efficiency combustion of fuel and, consequently, to obtain high technical and economic indicators of the diesel, it is necessary to organize a rational mixture formation. The quality of fuel spraying is characterized by its fineness and uniformity. It is necessary to organize the process of jet disintegration so as to obtain a high quality of spraying at all stages of injection, including the initial and final, when there is a low level of fuel pressure in front of the nozzle. A quality atomization requires continuous flow at a high pressure upstream the holes in the atomizer. Compliance with the fuel injection law, i.e. distribution of the crankshaft angle cycle charge in different ICE modes requires a wide flow variation range. The assumed priority of the requirements of the fuel injection law in systems employs variable pressure, including in the Common Rail systems [1,2]. Electrohydraulic injectors (EHI) in these systems are intended for implementing a multicycle injection with the number of cycles and duty ratio being limited by the speed of the injector. Partial limitation of the operation speed is due to the injector flexibility in terms of its operating pressures. The consequence of insufficient operating speed is deviation of the real injection conditions from the requirement [3-5].

2. Constant pressure high-speed injection nozzle

The electrohydraulic injectors include:
- an actuator in the form of a needle with a multiplier representing a hydraulic cylinder with the working chamber diameter exceeding the needle diameter and constituting a control chamber, and the needle spring representing a sealing device in the absence of the operating pressure;
- a pressure control device in the control chamber of the multiplier in the form of a slider or a valve with a solenoid drive.

![Figure 1. The EHI diagram:](image)

The valve 4 is small-sized, and therefore it is a high-speed valve since the main flow of the injected fuel does not pass through it. On the other side, the movement of the needle 7 is driven by the hydraulic force of the valve. The valve is located on the discharge side, which facilitates its layout, preserves the possibility of cooling, reduces the requirements for its hydraulic tightness and reduces the power necessary for control. The end solenoid 1 with the disk armature 3 opens the ball valve 4 by overcoming the spring 2. The pressure from the top of the multiplier decreases, and the needle opens the passage to the injector orifices 8. After the solenoid 1 is deenergized and the valve resetting, the pressure to the right of the multiplier is restored through the atomizing jet (Figure 1).

The following components may be referred to the structural features of the injector: Spring 5, multiplier, needle 7. The needle spring for the injector operation is mandatory and shall be installed around the multiplier to prevent the valve from reopening due to pressure waves when resetting. The closing multiplier increases the closing force acting on the needle. Unlike pressure-driven closing when the pressure is applied to the full area of the needle, this design allows for a large range of closing forces with the same pressure change. The inertia of the multiplier slightly impairs the system response. Also, the multiplier forms a precision pair with the case and increases the dimensions. Its main purpose is that increasing the ratio of the multiplier diameter to the diameter of the needle makes the process more controllable, accurate, and shorter.

When fuel is injected, the multiplier, with its upper end, tends to close the axial orifice leading to the ball valve 4. It may not be fully realized, since high pressure is restored through the jet and the multiplier is force up to the orifice. However, there is a real benefit from this equilibrium stabilization process: fuel flow for control becomes limited (from the battery through the jet, valve to drain).

The multiplier is a needle extension with a spring. From the point of view of the operating speed, it is an increase of the moving mass. The need to use the multiplier is stipulated by its suitability for a wide range of operating pressures.
The needle closing multiplier results in increasing the closing force with the same pressure acting in the control chamber and, thus, accelerating the needle closing. Even considering the weighting of the mass moving with the needle, the operating speed increases. The EHI is unserviceable for a high-speed diesel if the closing multiplier is omitted. Even if it is possible to ensure its operability, the delivery stability is low with respect to the wave processes, process deviations, etc.

The increase in the speed of the EHI ensures a shorter delivery time and, consequently, mean injection pressure and control flow, a reduction of the minimum stable delivery. At first glance, closing of the needle without the multiplier may be accelerated by tightening the spring, but the fundamental difference of this solution is the constant closing force, i.e. with the accelerated closing, opening will be decelerated as well. Therefore, an equally efficient structure may not be obtained by increasing the mechanical closing force of the needle as compared to the multiplier; and in case of low effort, the EHI becomes unstable.

According to the known results of the study [6] of the EHI the speed limitation is conditioned by a wide range of injection pressures, as well as by deviation of the real supply conditions from the requirement. However, the above statement is invalid regarding the EHI operating at a constantly high pressure. Transition to a constant pressure allows considering several options for increasing the injector operating speed:

1) increasing the rigidity and tension of the return spring, which gives it an additional compensating function as applied to the growing needle opening force acting on the tip of the needle;

2) decreasing the diameter of the multiplier piston with the corresponding decrease in the volume of the control chamber;

3) reducing the cross-sections of the bypass throttle and the sealing section of the control valve, with a corresponding additional reduction in the traction force and an increase in the operating speed of the solenoid valve.

To analyse the above possibilities for increasing the operating speed, the one-dimensional LMS Imagine.Lab AMESim [7,8] package was selected. Bosch 0445110190 electrohydraulic injector with a solenoid control valve and the dimensions of the seat, contact part of the needle and the outlets (Table 1), corresponding to the atomizer of the YAZDA 33.1112010-03 serial injector for the KamAZ-7409 engine was selected as the initial design of the model (Fig. 2). According to the assumed method, simulation was performed using models with an operating inlet pressure of 100 MPa.

Table 1. Injector model parameters

| Model component in LMS AMESim | Bosch | A modified model |
|-------------------------------|-------|-----------------|
| BAP12-2 + BAF01-1 | Multiplier diameter, mm | 4.3 | 2.5 |
| BAP015-1 | spring: | Pretensioning, N | 30 | 60 |
| | | Force, N/mm | 13 | 15000 |

Detailed parameters of the model are given in table 2,

Table 2. Detailed injector model parameters

| Model component in LMS AMESim | Component description | A modified model | Bosch |
|-------------------------------|-----------------------|-----------------|-------|
| Component | Description                      | Value          |
|-----------|----------------------------------|----------------|
| MAS005-1  | mass lower displacement limit     | 3 g            |
|           | lower displacement limit          | 0 mm           |
|           |                                  | 0.052 mm       |
| BAP24-1   | seat diameter (hole)              | 0.75 mm        |
|           | seat semi-angle                   | 57.5 degree    |
|           | ball diameter                     | 1.4 mm         |
| BAP12-2   | piston diameter                   | 2.5 mm         |
|           | rod diameter                       | 0 mm           |
|           |                                  | 4.3 mm         |
|           |                                  | 0 mm           |
| BAF01-1   | external piston diameter          | 2.5 mm         |
|           | clearance on diameter             | 0.003 mm       |
|           |                                  | 4.3 mm         |
|           |                                  | 0.003 mm       |
| MAS005-1  | mass lower displacement limit     | 6 g            |
|           | lower displacement limit          | 0 mm           |
|           |                                  | 0.05 mm        |
| BAP015-1  | piston diameter                   | 4 mm           |
|           | rod diameter                       | 0 mm           |
|           | spring force                       | 60 N           |
|           | spring stiffness                   | 15000 N/mm     |
|           |                                  | 30 N           |
|           |                                  | 13 N/mm        |
| BAF02-1   | external piston diameter          | 4 mm           |
|           | clearance on diameter             | 0.01 mm        |
| BAP12-1   | piston diameter                   | 4 mm           |
|           | rod diameter                       | 3 mm           |
| BAN004-1  | diameter of poppet                 | 3 mm           |
|           | diameter of sac chamber            | 2.99 mm        |
|           | number of orifices                 | 6              |
|           | orifice diameter                   | 0.12 mm        |
Following the calculation results, the diagrams were obtained as shown in fig. 3 and fig. 4. The data are compared against the cycle dose value for the same control signal, moreover, it should be considered that the higher the dose, the faster the response.

Following the results of measurements given in the diagrams at fig. 3 and fig. 4, the injector operating speed has observably increased. In this regard, further research will consist in analysing the influence of other factors and optimizing their values in order to obtain the maximum operating speed.
3. Conclusions
Further studies to improve the speed of the injector will be made using the described method. The process efficiency will be assessed by the full short-time opening mode of the Bosch injector and the modernized injector. The modernized injector should provide a smaller cycle dose in the modes of short-time full opening, while it will be possible to reduce the duty ratio between the injections.

Based on the simulation results, it can be concluded that the cycle dose should be reduced in the short-time full opening mode, while it will be possible to reduce the duty cycle between injections. In this connection, the research shall be continued with respect to the rest of the factors and optimization of their values to obtain the maximum operating speed.

The most promising for increasing the speed of injectors are the following activities:

1) Coordination of forces acting on the needle in order to reduce the required effort of the electromagnet. This matching allows the use of well-designed low-power high-speed electromagnets and their power devices in high-performance injectors. The peculiarity of this coordination process is its essential dependence on the tightness requirements, since the force of sealing the needle along the saddle is, in fact, the calculated force of the electromagnetic drive and can be significantly reduced. For example, the force of the nozzle solenoid valve control valve can be reduced by an order of magnitude.

2) Elastic coupling of the drive to the needle. This connection allows you to achieve the effect of multiplication, when large needle strokes without the use of mechanical or hydraulic transmission devices are provided by small moves of the electromagnet drive. At the same time, a reduction in the working stroke of a drive of any type ensures an increase in its speed.

3) Application of springs of rod type. Such springs provide the maximum level of material utilization efficiency for the accumulation of deformation energy. Rod springs provide minimum values of moving masses and extend the possibilities of arrangement of injectors.

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