Modelling Fuel System Injector Hydro-Mechanical Processes

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Abstract. This study analysed the characteristics of the fuel system of a self-ignition engine with electronic control, taking into account the characteristics of the processes in the injector and the injection control system. The results of simulations of hydro-mechanical processes in an injector with an electromagnetic controller are presented. The proposed model takes into account the propagation processes of the pressure impulse in the fuel and in the parts of the injector subjected to deformation during injection. To describe the elastically-deformable state of the injector parts, an equivalent model of the injector valve stem was used. The results of calculations are proposed for a common simulation of hydrodynamic and electro-dynamic processes occurring during fuel injection into the Common Rail (CR) system.

1. Introduction

Currently, fuel systems with electronic control are almost exclusively used in combustion engines. At the same time, research is ongoing to improve existing solutions, increase the reliability of components of this system, particularly of the CR-type electromagnetic injector [1].

This paper presents the mathematical model of the injector, which differs from other models in a number of original solutions. In hydro-mechanical fuel systems with direct injection [1], the time interval during which the elementary injection process is carried out is 0.05 - 0.1 ms, and for systems with electronic control, transient processes that are carried out in the injector volume, take a few microseconds. It follows that it is impossible to use known calculation methods to model CR injection systems [1, 2], without their proper adaptation. For a description of hydro-mechanical processes in the feed system with electronic control, dynamic models should be applied, which take into account the value of electromagnet force, fuel pressure in the injector volume, as well as the speed of displacement of the needle, control valve and anchor.

Research into injection processes with electronic control is also presented in the paper [3]. Modelling of the displacement of injector parts takes place with regard to elasticity and damping parameters. Differential equations were solved using the implicit scheme used for modelling rigid systems. The method of calculating the fuel flow in the pipeline using the Lax-Friedrichs method is also presented [4].

Other studies have examined modelling the fuel injection process using the AMESim program [5, 6]. Higher modelling accuracy can be achieved considering the degree of deformation of the injector piston and the phenomenon of cavitations [7, 8]. The results of the theoretical and experimental research on pressure conversion in the injector input cross-section occurring during the fuel injection seems to be valuable in this work.

In the AVL HYDSIM program [9], the calculation of the hydrodynamic process was proposed using the Godunov method. Using this method allows to map most of the factors that occur in the real hydrodynamic process. This method may also be used for the modelling and calculation of fuel equipment with electronic control [10].
2. Objective and scope of the study

The objective of the study is to develop a mathematical model of hydrodynamic processes that occur in an injector with electronic control. The modelling takes into account factors that affect the transformation of the fuel pressure in the injector's volumes, as well as the displacement speed of the needle, control valve and anchor (figure 1).

To develop a method for calculating the parameters of a fuel system, a mathematical model is necessary, and its basis is a hydro-mechanical scheme (figure 1). This diagram takes into account changes in fuel pressure in the control chamber \( P_s \) and, in the storage tank \( P_z \), the displacement values of the anchor \( h_k \), the anchor silencer \( h_{ho} \), valve \( h_z \), bucket increaser \( h_t \) and needle \( h_i \).

Determining the displacement characteristics of the injector valve requires knowledge of the Fm force value of the magnetic field of the electromagnet, which changes during the injection, depending on the current value, the distance between the anchor and the core and the speed of the anchor displacement.

3. Mathematical model of the injector

3.1. Fuel flow

The fuel flow parameters in the high pressure duct are determined by the following equation [4]:

\[
\frac{\partial^2 c(x,t)}{\partial t^2} - a^2 \frac{\partial^2 c(x,t)}{\partial x^2} + K_c \frac{\partial c(x,t)}{\partial t} = 0
\]

where: \( C(x, t) \) - fuel flow speed, \( t \) - time, \( x \) - coordinate of the distance in the high - pressure duct, \( K \) - hydrodynamic drag coefficient, \( \alpha \) - velocity of pressure wave propagation in the fuel.

In the solution of equation (1), the method of characteristics is used [11]. The assumptions made in the diagram (figure 1) require the modernization of this method. In the fuel system [1, 2], for which the method of characteristics has been developed, the pressure impulse spreads from the pump to the injector (in one direction). This determines the order according to which the volume of the system is calculated.

Analyzing the hydro-mechanical scheme of the CR injector (figure 1), it should be noted that the pressure impulse moves from control chamber \( B \) to volume \( C \) via two paths:

- an injector piston/valve spindle and needle in the form of an elastic wave at a speed of about 5 m/ms;
- in the high pressure duct at a speed of about 1.4 m/ms.

From that, it follows that pressure waves reach the atomizer at different times. The second important feature of the scheme is that the injection process is controlled not in the fuel reservoir \( A \) but in the chamber \( B \).

In the modernized method of characteristics (figure 2), two initial points corresponding to the control volume \( B \) and the atomizer \( C \) are determined. The channel between these volumes is divided into two sections of equal length. At the point where these segments connect, there is pressure of \( P_z \). At this point, the condition of pressure continuity and fuel flow velocity is assumed.

In the first section of the high-pressure channel there is a tee, which is the beginning of additional characteristics that lead to the volume \( A \) (up to the pressure \( P_z \)). The actual waveforms of the characteristics will be disturbed by the locally variable value of the speed of sound. The solution of the problem regarding the flow of fuel in the high pressure duct requires consideration of the initial and final conditions. The following initial conditions were adopted (ignoring the fuel return): the fuel flow velocity is zero, the fuel pressure in the \( A \), \( B \), and \( C \) volume are equal to the pressure of \( P_z \). The final conditions are determined by differential equations of the effected fuel flow rate (effected fuel portions) balance in the injector volumes and the equations of movement of the needle, the injector piston/valve spindle and the valve taking into account their deformation. In the volumes of high pressure \( A \), \( C \), \( B \) the compressibility of the fuel is also considered. In the low pressure \( E \), \( K \), \( L \) volumes, the fuel inertia
is taken into consideration when the valve, anchor and silencer displace. This is related to the existing adhesion forces between the fuel and the surfaces of the injector parts. It is therefore necessary to take into account the mass of adhering fuel to these parts during their movement.

Figure 1. Hydro-mechanical scheme of the CR injector.

Figure 2. Network of characteristics used for equation (2) calculations.

3.2. Modelling of elastic elements
The spring stress (needle, check valve and silencer) is determined taking into account the variability of their turns, to which the equivalent model of the valve stem is used [12] and its analytical equations. Analogous models are used to describe the elastically-deformable condition of the needle, the injector piston/valve spindle and the control valve stem.

Equations for calculating the response \( q \) in springs and injector pistons/valve spindles with fluctuation records take the following form:

\[
q(t) = z^2 \left( h_0 + 0.5 \Delta h_1(t) + \sum_{j=1}^{\infty} \frac{df}{jT_s} \cdot \Delta h_1(t - jT_s) - 0.5 \cdot (1 + df) \times \sum_{j=0}^{\infty} \frac{df}{(j+0.5)T_s} \cdot \Delta h_1(t - (j+0.5)T_s) \right)
\]

\[
\Delta h_{1,2}(t) = \left( T_s \cdot \dot{h}_{1,2}(t) + \frac{2(1-df)}{1+df} \cdot h_{1,2}(t) \right)
\]  

(2)

where: \( m \) - mass; \( z \) - coefficient of elasticity; \( T_s \) - basic period of variation; \( df = 0.9 \ldots 0.97 \) - damping decrement; \( h_0 \) - initial deformation; \( h_{1,2}(t) \) - displacement of end cross-sections.

4. Application of modelling
Based on the obtained calculation results (figure 3) it can be concluded that the deformation of the injector piston \( \Delta h \) (0.17 - 0.2 mm) corresponds to the needle displacement (0.25 mm).

In the work [5] it was indicated that the deformation of the injector piston is 36% when displacing the needle caused by pressure in the fuel reservoir of 140 MPa. The omission of the causes of this
deformation leads to an error in determining the initial moment of displacement of the needle. In works [3, 5, 13], the causes of failure sections (or small steepness of the graph, as shown in figure 4) were identified in the fuel flow rate characteristics. The authors of the indicated works see the reasons for this effect in changing the dynamics of the valve's movement at the turning point, in wave processes in the pipeline and in the presence or absence of the needle reaching its seat.

The obtained results also show that unstable injection may be the result of deformation of the ‘injector piston’ and ‘valve stem’.

These factors were taken into account for the development of a mathematical model, which was used in the analysis of hydrodynamic processes occurring in the Bosch injector [1]. Selected results of process modelling, at a fuel reservoir pressure of 143 MPa, are shown in Figure 6. Based on this model, a method and program for dynamic calculations have been developed.

The application of this method allowed the main criteria for the selection of CR injector construction parameters to be determined, as well as to identify the occurring damages, which contributes to increasing the reliability of the injector design.

The conducted research shows that the asymmetry of the magnetic chain reduces the impact of inaccuracy in the manufacture of the injector elements on the valve's motion characteristics.

In order to reduce the impact of eddy currents, the shape of the anchor can be modified by introducing cuts (grooves in its foot). In order to maintain the stability of the injection process, it is necessary to limit the speed of the valve movement during the impact of the cone lock on the bottom of the sleeve. It should also be noted that the anchor seat design used in multi-phase injection is of a low affectivity.

Effective electronic control of the injector is possible only when the control chain, solenoid and hydrodynamic characteristics are taken jointly into account. At the same time, as noted in [6], the criteria of efficiency cannot only take into account whether the required injection intensity is achieved, but it must also consider the stability of the main indicators and reliability of the fuel system.

The above problem can be solved by calculating the change of magnetic chain properties [14] and the control algorithm. While controlling the short fuel injection pulse, the control valve must move at maximum speed, and after the valve has hit against its seat, the magnetic field attraction force must be reduced to zero.

When controlling by the main pulse, the valve should set at a low speed, thus being protected against damage. In addition, the supporting current shall be corrected by taking into account the fuel pressure in the reservoir and the magnetic chain shall be designed by taking into account the necessary reserve of the magnetic force.
5. Conclusion
A method and program for calculating hydrodynamic phenomena occurring during the operation of an electronically controlled injector were developed.

To determine the flow of fuel in the pipe, a modernized method of characteristics was used, which takes into account the hydraulic properties of the injector.

The stem equivalent model was used for determination of the elastically-deformable state of the needle, bucket increaser and the valve stem as well as for calculation of the stress of springs.

The main principles for the selection of the injector construction parameters were also established. In order to increase the injection pressure, it was proposed to use wave processes that exist in the tubing connecting the fuel reservoir with the injector.

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