NUMERICAL MODEL OF COMMON RAIL ELECTROMAGNETIC FUEL INJECTOR

Stasys Slavinskas[1], Gvidonas Labeckas[1], Irena Kanapkiene[1],Tomas Mickevicius[2]
[1]AleksandrasStulginskis University, Lithuania;
[2]Kaunas University of Applied Engineering Sciences, Lithuania
stasys.slavinskas@asu.lt, gvidonas.labeckas@asu.lt, irena.kanapkiene@asu.lt,
t.mickevicius@yahoo.com

Abstract. The injection process in diesel engines has influence on the in-cylinder combustible mixture formation, ignition, combustion, and exhaust of emissions. Modern diesel engine injection system is under strict requirements to fulfil the purpose to not only reduce the fuel consumption but also the exhaust emissions and noise levels. The Common Rail injection system gives engine developers the possibility to reduce both exhaust emissions and engine noise. The Common Rail (CR) fuel injection system allows accurately regulating of the fuel injection rate, the rate of fuel discharge from the nozzle holes, distribution and timing with the engine operating within a wide range of loads and speeds. The CR fuel injection system with piezo or electromagnetic nozzles speeds up the nozzle opening and closing, allowing adjusting the injection pressure, injection rate and atomisation characteristics. This paper presents numerical modelling of injection characteristics in a diesel engine. The numerical model was performed by using AVL BOOST Hydsim fluid dynamic simulation. The experiment results were compared with the numerical ones. The injection characteristics were measured and analysed using the injection rate measuring system. The injection rate, injection quantity per cycle, injection delay, and injection duration were analysed across a range of injection pressure and injection energizing time. The comparison of the results shows that the numerical model is reliable and the results of the numerical model are close to the experimental test results.

Keywords: common rail fuel injection, injection rate characteristics, numerical simulation.

Introduction

In recent decades, the scientists have considered how to rationally address problems concerning sensible use of global energy and the environment. Until now, researchers have not offered new technological solutions to completely replace internal combustion engines with other sources of mechanical energy. The steady growth in the number of motor vehicles on the world's roads continues to increase the annual fuel consumption and a necessity to produce more fuel from crude oil. It is also important that oil-based fuels are extracted from limited resources with production concentrated only in certain regions of the world. The increasing demand for mineral fuel is not only depleting the global oil reserves, but also contributes to air pollution and exacerbates the global warming caused by carbon dioxide. In the EU, transport accounts for 21 % of all greenhouse gases contributing to global warming, and this figure is constantly growing. Therefore, a "White Paper" development plan was created for the entire European transport area, some of encouraging trends are under development and the use of sustainable fuels increases the efficiency of all modes of transport energy and suggests a 60 % reduction in emissions in the transport sector.

Diesel fuel is one of the most popular types of motor fuels. The consumption of this type of fuel has been increased several-folds over the past decades with the increased use of heavy trucks and passenger vehicles. In order to reduce the fuel consumption and follow stricter permissible standards for exhaust emissions and noise, the modern diesel engine injection systems must be subjected to new requirements. The Common Rail (CR) fuel injection system allows better regulation of the fuel injection rate and injection time, the amount of fuel discharged from the nozzle holes, and fuel distribution when running the engine across a wide range of loads and speeds. The CR fuel injection system, equipped with its piezoelectric or electromagnetic injectors, accelerates the opening and closing of the nozzle that allows regulating the injection pressure, injection rate and injection characteristics. The increased average injection pressure accelerates the supply of fuel to the combustion chamber, which, in turn, ensures better injection quality of the fuel entering into the combustion chamber and shortens the duration of premixed combustion. Scientists have observed that higher injection pressure and intensive turbulence of the air charge improve the formation of the combustible air and fuel mixture [1]. Using of a high-pressure injection system reduces the formation of nitrogen oxides and particulate matters during combustion and engine noise because of more accurate control of the injection pressure, injection speed and the ignition advance BTDC [2]. The engine efficiency and dynamics of the combustion process are directly related to the regulation of the characteristics of fuel injection into the cylinder, warm up, evaporation, combustible mixture formation and fuel heat release during combustion [3].

Scientists have noted [4]that the currently used fuel injection system and the physical-chemical properties of the fuel affect the combustion process in a diesel engine and the formation of exhaust emissions in the cylinder. Most of the authors only analysed the engine performance and exhaust emissions, therefore, there is a lack of more detailed research to explore the impact of the physical parameters of the fuel on the ongoing processes in the common rail injection system. The effects of fuel density, viscosity, and elasticity modulus during the hydrodynamic processes in a high-pressure injection system at increasing pressure are of great importance to the fuel injection process.

Examination of the fuel injection process parameters is not always possible without mathematical modelling of the injection system. Such models save time, help simplify the research process and are an effective means for forecasting the dynamics of the injection process variables [5]. The effect of the injection parameters on the characteristics of dimethyl ether (DME) was investigated by using of experimental and analytical models based on empirical equations of Suh et al. [6]. The researchers found that calculation results based on empirical equations provide good agreement with experimental results. Using the AMESim software package Seykens et al. [2] prepared a mathematical model of the common rail injection system and performed experimental studies. The obtained results were compared with those measured experimentally. The simulation tests showed that the resulting mathematical model was reliable because it predicts the experimental results with accepted accuracy. Boudy et al. [7] studied the impact of the physical properties of biofuel on the fuel injection process characteristics. The fuel physical properties were changed in each simulation test and the obtained numerical simulation results were compared with the experimental ones.

Gupta et al. [8]studied and analysed pressure pulsation inside the CR injection system. The aim of the work was to create a new mechanism that would reduce pressure pulsation in the fuel tube. As the result of his study, the experimental and the mathematical modelling simulation-results were very similar that shows the model is reliable. Sun et al. [9] studied the fuel injection characteristics by using a simulation model. The modelling was performed using a cavitation method. Analysing the modelling results, the authors noted that when the needle is rising, the amount of fuel injected and the fuel permeability coefficient increase. This is due to the impact of the parameters controlling the fuel flow at the beginning of the process, the flow is affected by the effective cross-sectional area and then it is controlled by pressure, which builds up in front of the nozzle hole inlet opening. Salvador et al. [10] mathematically modelled the internal flow and cavitation in the diesel engine nozzle spray holes at different needle lifting heights using 3-D simulations. The results showed that different needle lifting heights differently affect the cavitation process. By using a numerical method, Brusiani et al. [11] investigated short-term cavitation in a diesel injector at different injection pressures.

In order to find out which way would be the most promising for improving the injection process in the CR injection system it would be expedient to apply the numerical model in a broader manner.

Materials and methods

The injection characteristics measurement was carried out on a high pressure Common Rail fuel injection system. The fuel injection system included a high pressure pump, a rail, injector and electronic unit to control the injection pressure. The injector nozzle has 6-holes and the diameter of each hole is 0.24 mm. Injector was controlled by a peak current of 26.0 A. and a holding current of 14.0 A.

The fuel injection rates were measured according to the Bosch method [12]. The injection rate measuring system included an adapter for mounting of the injector, a measuring tube 6 m in length, orifice, following tube and a check valve. The injection rate measuring method was based on measuring dynamic increase in pressure produced by the fuel injection into the measuring tube filled with fuel. The increase of the dynamic pressure is proportional to the injection rate [14].

The fuels have been injected with the following pressures: 25.0 MPa and 80.0 MPa. The injection duration was 2.6 ms and 1.1 ms. The back-pressure in the injection tube was adjusted to 4.0 MPa in order to simulate injection pressure corresponding to a real value of the pressure in the combustion chamber of an engine.

Numerical simulation of the injection process was carried out with AVL BOOST Hydsim software (version 2013.1) for dynamic analysis of hydraulic and hydraulic-mechanical systems. Hydsim BOOST program was designed for diesel injection system modelling. Currently this software has been improved and adapted for simulation of all types of injection systems, using both traditional and alternative fuels. BOOST Hydsim is a software tool for integrated systems including mechanical, electrical, thermal, hydraulic and other components. It is a 1–D simulation program, which uses libraries to describe each component of the system. Generally, the program is useful in a variety of fields concerned with dynamic analysis of hydraulic, mechanical and control systems. For instance, using MATLAB interface, BOOST Hydsim can simulate the dynamics of hydro-mechanical control devices, such as for the engine inlet and exhaust valve lift control, and the vibration of drives (AVL Boost Hydsim, 2013) [13].

Figure 1 presents the electromagnet-operated nozzle and its main components used in the spray modelling. Table 1 shows the key parameters of the spray elements required for modelling. Injection characteristics obtained with the numerical model are compared with those measured during the experimental study.

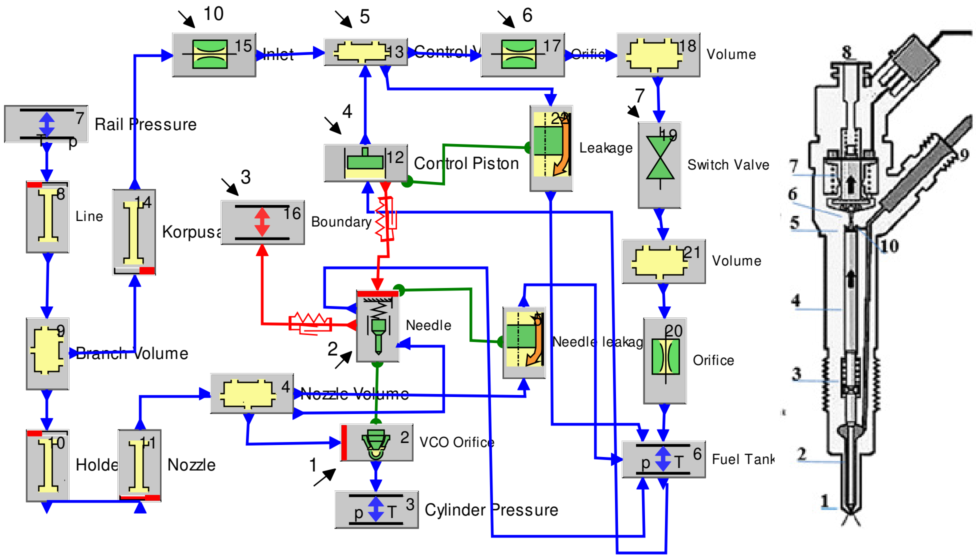

Fig. 1. **Numerical model scheme of electromagnetic BOSCH injector:** 1 – nozzle; 2 – nozzle needle; 3 – nozzle spring; 4 – control piston; 5 – control chamber; 6 – outlet throttle; 7 –electromagnet; 8 – fuel outlet; 9 – high-pressure-jung expected; 10 – inlet throttle

Volumetric flow rate (injection rate) through Nozzle Orifice is calculated from Bernoulli equation:

$$\dot{Q} = \mathrm{sign}\left(p_{in} - p_{out}\right)\sqrt{\frac{1}{\frac{1}{Cd_{nsh}^2 A_{nsh}^2} + \frac{1}{Cd_{hole}^2 A_{holes}^2}}}\sqrt{\frac{2}{\rho}\left|p_{in} - p_{out}\right|}, \tag{1}$$

where $\dot{Q}$ – injection rate, $m^3 \cdot s^{-1}$;
Cd_{hole}–flow discharge coefficient in the spray hole;
A_{nsh} –total narrowest flow area before nozzle spray holes, m^2;
Cd_{nsh} – flow discharge coefficient in the area before the nozzlespray hole;
A_{holes}–open cross-sectional flow areas of sprayholes, m^2;
p_{in} and p_{out}–pressures on input and output, Pa;
ρ–fluid density, $kg \cdot m^{-3}$.

Actually, $p_{in}$is the pressure in the nozzle volume while $p_{out}$is the pressure in the injection chamber. For direct injection engines, $p_{out}$is the in-cylinder pressure.

Mass flow rate through nozzle orifice in time domain is calculated from the equation:

$$\dot{m} = Q\,\rho_D, \tag{2}$$

where $\dot{m}$ – mass injection rate, mg·ms^{-1};
Q – flow rate, mm^3·ms^{-1};
ρ_D – liquid density, mg·mm^{-3}.

Table 1

Main component parameters of the nozzle

Parameter	**Value**
Nozzle holes	6
Specify diameter of one spray hole	0.24 mm
Specify length of one spray hole	1.3 mm
Nozzle diameter at spray holes	1.65 mm
Needle mass	0.00417 kg
Needle guide diameter	0.004 m
Needle seat diameter	0.0023 m
Maximum lift of needle	0.00028 m
Piston moving mass	0.008 kg
Piston input end diameter	0.0043 m
Initial volume	2 10^{-8} m^3
Throttle cross-section area	4.158 10^{-8} m^2
Spring stiffness	34900 N·m^{-1}

Pressure required for modelling in the fuel accumulator was obtained during the experimental studies by measuring the pressure changes in the high-pressure pipe to the fuel battery and the nozzle.

In order to analyse the effect of the injection characteristics diesel fuel (DF)was used in this study. Diesel fuel (class 1) was produced at the manufactory "OrlenLietuva" and its quality parameters satisfied the EN 590:2014+AC requirements.

Results and discussion

The numerical model validation has been carried out by comparing the injection characteristics and cyclical injected quantities of fuel obtained in the experimental studies and modelling. Fig. 2 shows the experimental and modelled injection characteristics when injecting diesel fuel at pressure of 25.0 MPa and 80 MPa.

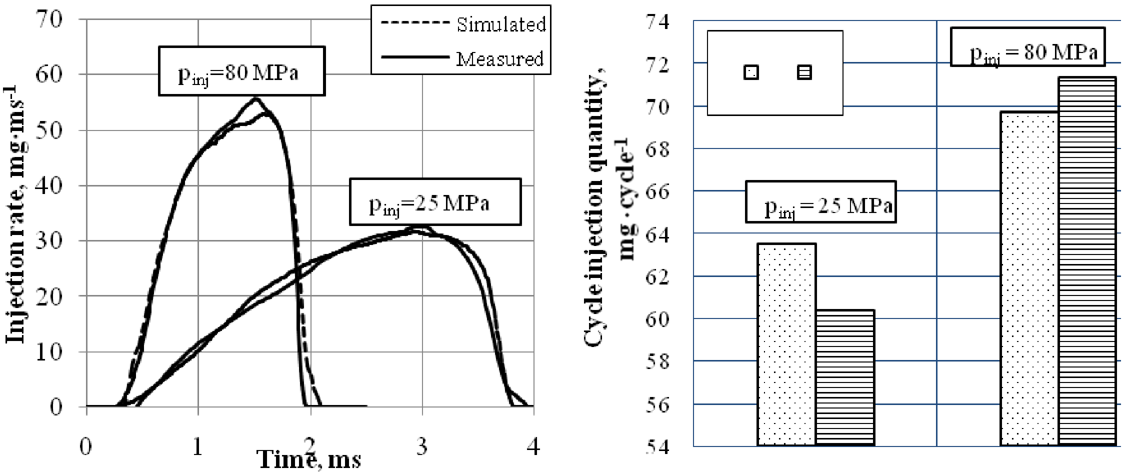

Fig. 2. **Injection characteristics and injection quantity per cycle of diesel fuels obtained experimentally and by simulation at the fuel injection pressure of 25 MPa and 80 MPa**

As graphs in Fig. 2 show, there is a good correlation of the numerical model results and the experimental findings. A good correlation results were also obtained for comparison of the diesel fuel injection characteristics measured at 80.0 MPa pressure.

The correctness of the numerical simulation results is confirmed by the obtained same fuel amounts delivered per cycle (Fig. 2). The maximum difference between the results of the experimental studies and modelling does not exceed 4 %.

Numerical simulation results allow the analysis in more details of different stages of the injection process. Figs. 3 and 4showthe fuel flow rates incoming to and outgoing from the control chamber and pressure variation in the chamber at pressures of 25.0 MPa and 80.0 MPa in the fuel accumulator.

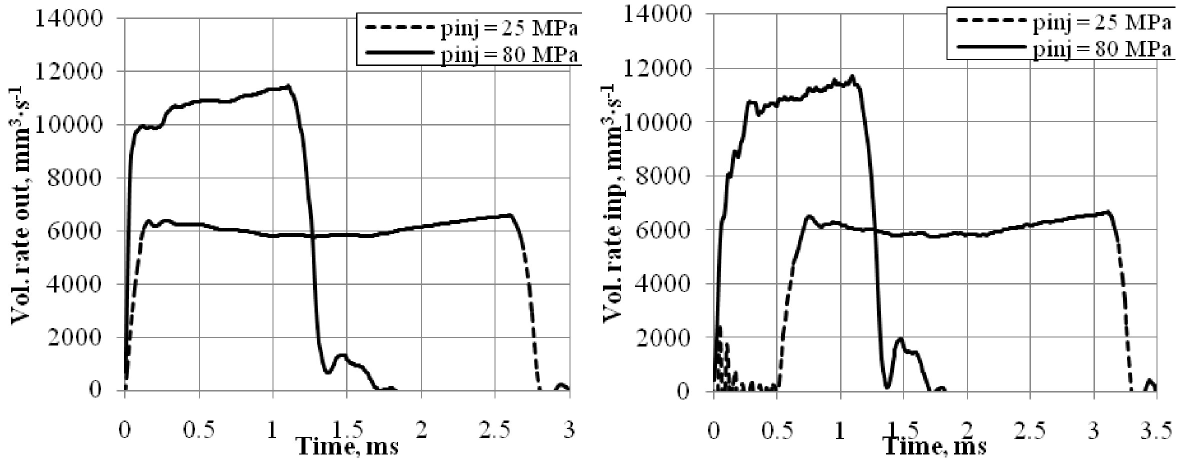

Fig. 3. **Volume rate output and input of Common Rail injector control chamber**

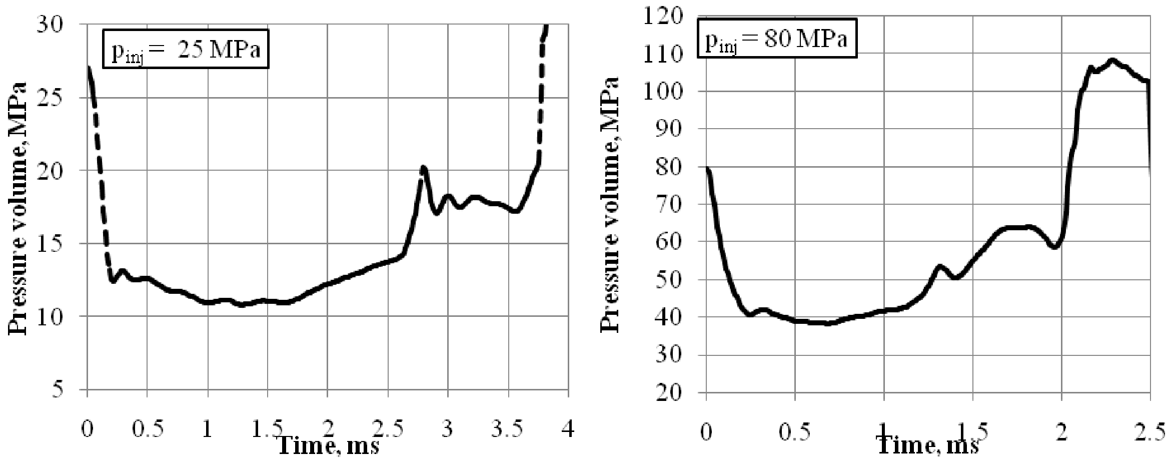

Fig. 4. **Pressure changes in the control chamber**

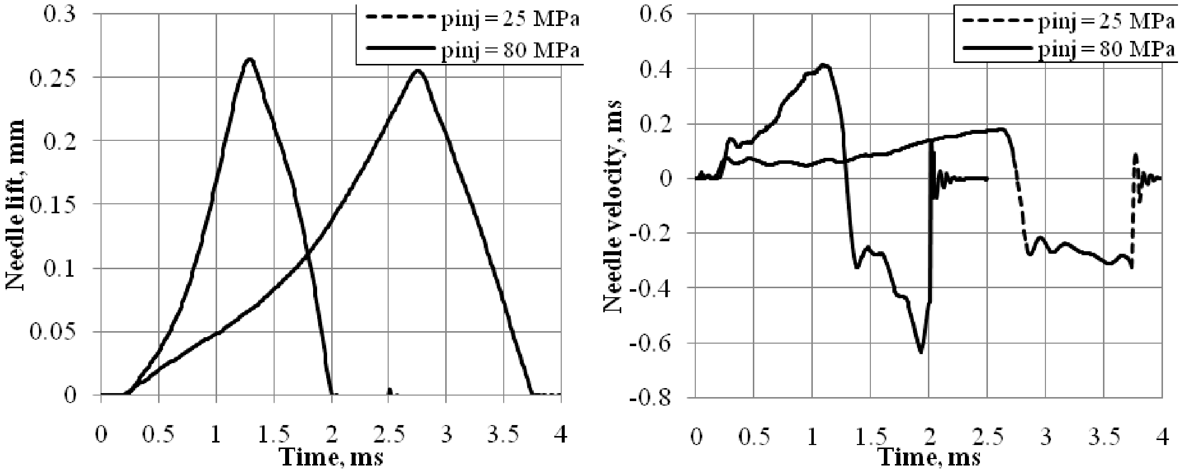

Fig. 5. **Nozzle needle lift and velocity**

When the electromagnetic control valve opens the outflow throttle of the control chamber, the pressure in the control chamber falls down (Fig. 4). The pressure variation is affected by the fuel flow rates incoming and outgoing to/from the chamber (Fig. 3) and the displacement of the plunger, which changes the volume of the control chamber. As shown in the graphs of Fig. 4, the fuel pressure in the control chamber decreases with the increase of outgoing flows. Because of the increased pressure difference at the inlet throttle the fuel flow through it increases. When the pressure in the control chamber decreases, the nozzle starts to open and fuel injection again begins. The rising nozzle needle also lifts the control plunger. As soon as the volume of the control chamber decreases, the pressure in the control chamber slightly increases (Fig. 4). The lifting speed of the nozzle needle depends on the difference of the fuel flow through the inlet and the outlet throttles. When the electromagnetic valve closes, the outlet throttle pressure in the control chamber begins to rise again, however, because the control plunger starts to move up, the pressure is no longer increased until the nozzle is closed and the injection stops (Fig. 5).

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Conclusions

This article presents modelling methods of a Common Rail electromagnetic fuel injection by using AVL BOOST Hydsim software. The numerical model of the injector was prepared and the obtained simulation results were compared with the experimental injection results of diesel fuel with consideration to the fluid dynamic properties. The comparison of the results shows that the numerical model is reliable and the obtained numerical modelling results match well with the experimental test results.

The simulation model intends to alleviate detailed analysis of the CR fuel injection characteristics when using widely different physical properties of the fuel.

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