

## RESEARCH THE FUEL INJECTION CHARACTERISTICS OF A COMMON-RAIL SOLENOID INJECTOR

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### Abstract:

In this study a solenoid common-rail injector was investigated in order to achieve the fuel injection characteristics. This injector is designed by Delphi to be used in 2.0liters diesel engine for light-duty vehicle application. Firstly, an injector simulation model was developed in advanced simulation code AVL BOOST Hydsim. The geometrical parameters were taken from technical documentation while the mass parameters were measured. Secondly, an experimental study of the injector was conducted on the injector's test bench according Delphi test procedure at three injection pressures. The injector model was validated as simulated and measured injected delivery was compared at different injection duration. Finally, the rate of injection was estimated as a function of crank angle at different engine operating points as well as the influence of some geometric parameters on the injection process.

**Keywords:** *solenoid injector, common-rail, simulation, experimental test, rate of injection*

### 1. Introduction

Modeling the working process in the cylinder of internal combustion engines is a key point on the engines development phase. The combustion process in modern diesel engines is important in order to achieve compliance with emissions and CO<sub>2</sub> regulation demanded by EU. A number of combustion models have been presented over the years [1-3].

Over the last decades the phenomenological models are most commonly used in modern OD programs for prediction the rate of heat release in combustion chamber. The calculations are based on the real injection process including injection pressure, geometrical parameters of the nozzle and combustion chamber as well as fuel jet atomization and evaporation are taken into account. Typical phenomenological diesel combustion models are mixing controlled model [4-6], stationary gas jet model, packet models, and time scale models [5]. All of these models are based on the rate of injection (ROI). Although in modern diesel engines a common-rail fuel system with constant injection pressure is most commonly used the prediction of rate of injection is not a simple task.

The aim of this study is development of a simulation model of solenoid injector from direct injection diesel

fuel system which is proven by means of experimental values of the injected quantity.

### 2. Injector characteristics

#### 2.1. Design of injector under study

The injector which is objects of this study is a solenoid controlled, developed by Delphi. It belongs to an injector's generation DFI 1.3. This injector is used in PSA 2.0 HDI engines with a maximum power of 100kW at 4000rpm. The maximum injection pressure of the system is 1600 bar. The design of the injector is presented in Figure 1.

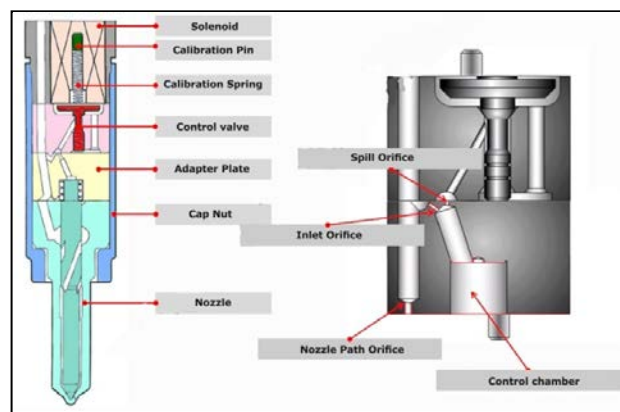


Figure 1. Design of common rail injector Delphi DFI 1.3

In order to develop an accurate simulation model it was necessary to obtain geometrical and mass parameters of the injector elements. Due to the fact that there was no comprehensive technical documentation from the manufacturer it was difficult to find out all information needed. In this case it was used an approach that some of parameters such as needle diameter, needle mass, etc. were measured. The other parameters such as number of injection holes, diameter of injection holes and the size of control chamber orifices were taken from technical documentation. However, some of parameters especially the volumes were unknown because there was not a possibility to be measured correctly. For that reason they were optimized at model calibration step in order to achieve minimum injected fuel deviation in comparison with experimental data. The main injector parameters used in the study are listed in Table 1.

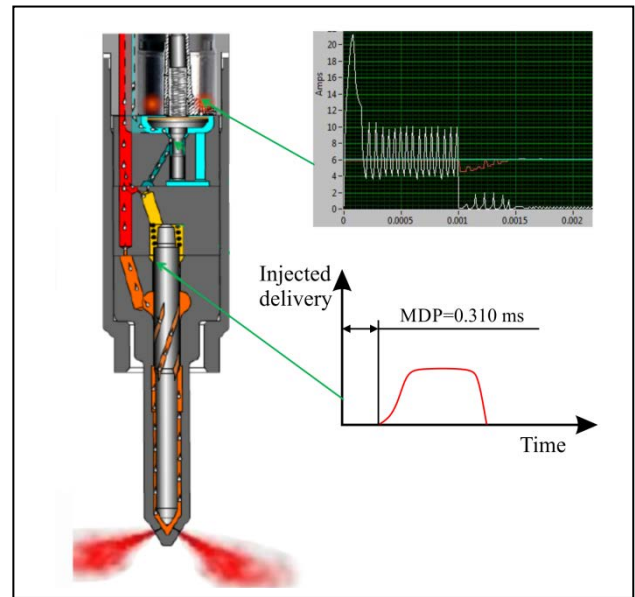
**Table 1. Injector main parameters**

Needle diameter	4.5mm
Needle seat diameter	1.7mm
Needle maximum lift	0.2mm
Nozzle holes	6
Nozzle hole diameter	0.15mm
Spring stiffness	35000N/m
Spring damping	20N.s/m
Nozzle volume	200mm <sup>3</sup>
Control volume	25mm <sup>3</sup>
Valve volume	15mm <sup>3</sup>
Nozzle path orifice	1 mm
Inlet orifice	0.25mm
Outlet orifice	0.2mm

## 2.2. Principle of operation

The solenoid injectors are controlled electro-hydraulically in order to provide minimum response time and precise control of the start of injection and injection duration. In order to reduce the response time high voltage is applied to the solenoid valve for a short period. It increases the current rapidly up to 22 Amps for these injectors. Respectively, the electromagnetic force is sufficient to open the control valve. After that period much lower force is needed to keep the valve open. Due to that the voltage applied varies in order to provide the current around 6 Amps.

However, the injection process does not start immediately after opening the control valve. Time is needed to pressure reduction in the control chamber which causes increasing hydraulic force for needle opening. It is observed by the manufacture that



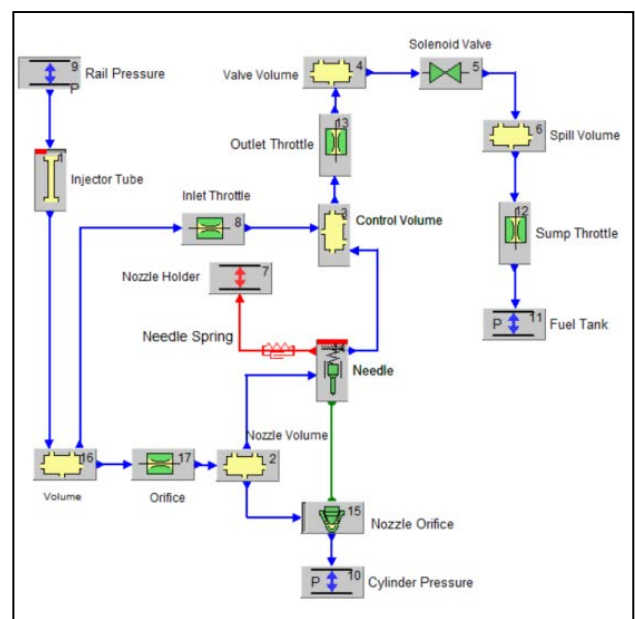
**Figure 2.** Injection process overview

injection delivery is delayed by 0.310 ms than beginning of electrical pulse at 1600 bar injection pressure and injection pulse of 1 ms. The injection process is presented in Figure 2. Although that fact, injection duration is approximately the same as electrical pulse. Usually, this delay has to be programmed in ECU of the engine.

## 3. Simulation model

The injector model was built in the advanced simulation code AVL Boost Hydsim using the available elements (Figure 3). The main elements used were the volumes, orifices, needle, nozzle, spring, valve, boundaries, and tubes.

In this model the solenoid valve was replaced by



**Figure 3.** Simulation model in AVL BOOST Hydsim

mechanical valve which opens and closes the cross section area in a way typical for solenoid valves. It was considered that cylinder pressure is equal to atmospheric pressure. It corresponds to experimental test condition where the injector is placed into the holder and the injected fuel goes to the flow meter at atmospheric pressure. Also, it was assumed that the injection pressure in the rail is a constant during the injection. Leakage through the needle was neglected in this study.

#### 4. Experimental setup

An injector taken from a brand new diesel engine was tested following the standard test procedure for CRI injectors. A test stand Hardrige CRI-PC which is recommended by Delphi for control of CRI injectors was used. The experimental test equipment is shown in Figure 4.

Delphi CRI test procedure includes measurement of injected quantity at constant injection pressure as a function of injection pulse. This test repeats several times at different pressure. Finally, the result is a family of measured curves which are compared with the curves of calibrated injector. Then, the variation in injected quantity in comparison with calibration values is written as an individual code of the injector. Usually, for correct operation of engines this code should be input to the engine ECU.

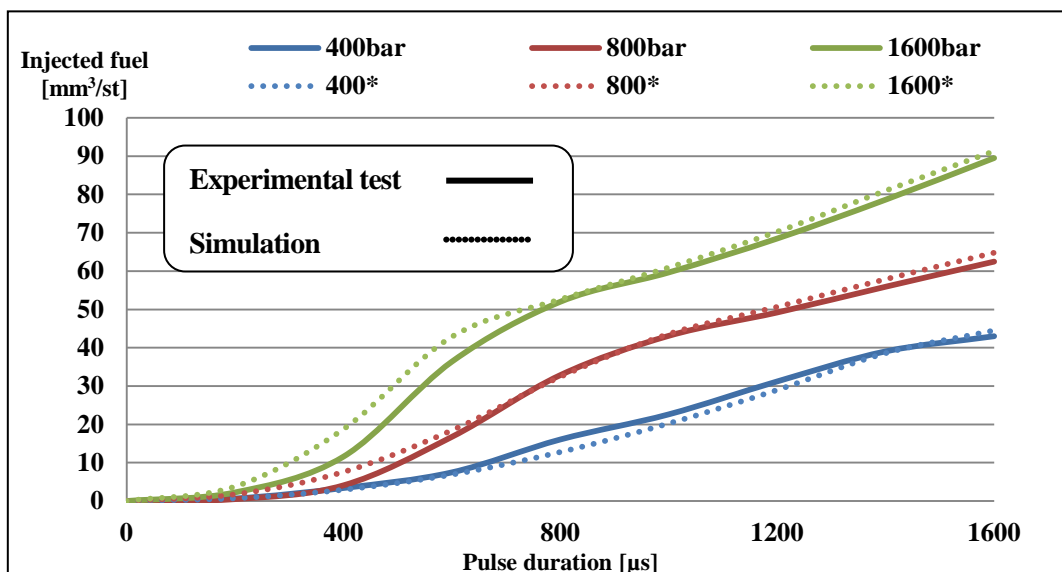
In this study it was not needed to evaluate the injector with a calibrated one due to the fact that the injector that was tested was new. The experimental research was needed to obtain the injected quantity as a function of injection pressure and pulse duration. It was assumed that the injected fuel is similar to calibration values.



**Figure 4.** Experimental test equipment

The experimental results were obtained with three injection pressure values – 400, 800 and 1600 bar. In order to calibrate the simulation model several geometric parameters such as control volume, needle volume and nozzle orifice were varied. Finally, the minimum deviation was observed with the values listed at Table 1. The results are presented in Figure 5.

At injection pressure value of 400 bar the maximum deviation was calculated to be 3.28 mm<sup>3</sup>/st for injection pulse of 800μs. The absolute value of deviation at 800 bar is approximately the same – 3.49 mm<sup>3</sup>/st. This deviation was observed at pulse duration



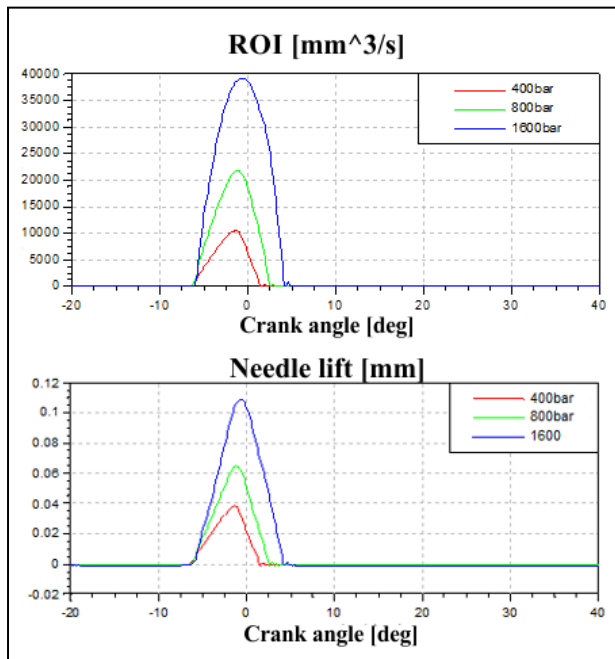
**Figure 5.** Injector model validation

equal to  $400\mu\text{s}$ . The highest deviation was found at 1600 bar injection pressure. The value was  $7.17\text{ mm}^3/\text{st}$ . The dispersion of injected quantity is typical for common-rail injector due to the fact that the injection process is very sensible of geometrical and mechanical parameters of the components. Usually, the mass production technology cannot provide more precise control of these components. That fact as well as the small deviation shown in Figure 5 allowed using the injector simulation model to determine the rate of injection (ROI).

## 5. Numerical results

### 5.1. Rate of injection simulation

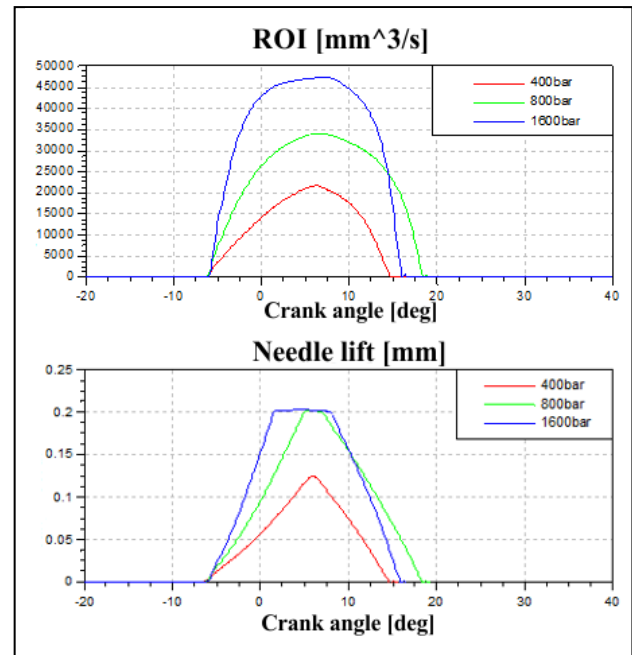
The main purpose of simulation model was determination the ROI in different operating condition of the engine. Thus, the combustion process can be studied by means of phenomenological combustion model. In this study ROI was estimated at several operating points of the injector. The operating condition was set up by combination of two values of injection duration and three values of injection pressure. The results are presented in Figure 6 and 7. ROI is estimated as a function of crank angle at constant speed.



**Figure 6.** ROI and needle lift at pulse duration  $400\mu\text{s}$

It was observed that at low pulse duration typical for low engine load the needle lift can not reach the maximum value even at injection pressure of 1600 bar. The maximum lift was estimated to be 0.11 mm. Although equal pulse duration the hydrodynamic processes into the injector causes different injection

duration. The highest injection duration was observed at 1600 bar.



**Figure 7.** ROI and needle lift at pulse duration  $1000\mu\text{s}$

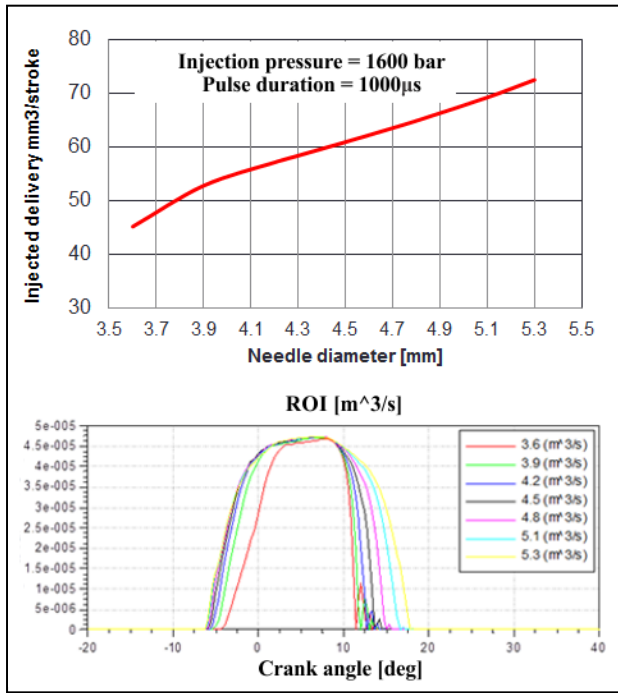
As is shown in Figure 7, the maximum needle lift of 0.2 mm is reached at injection pressure higher than 400 bar. This research was conducted with pulse duration of  $1000\mu\text{s}$ . These operating conditions are typical for medium and high engine load. It was also observed that injection pressure causes different injection duration. However, the maximum injection duration was not estimated at 1600 bar. Here, the highest value was at 800 bar.

Estimated ROI curves revealed that a plateau interval increases as a function of pulse duration and injection pressure. At that operating condition where maximum needle lift is not reached the ROI shape is triangular.

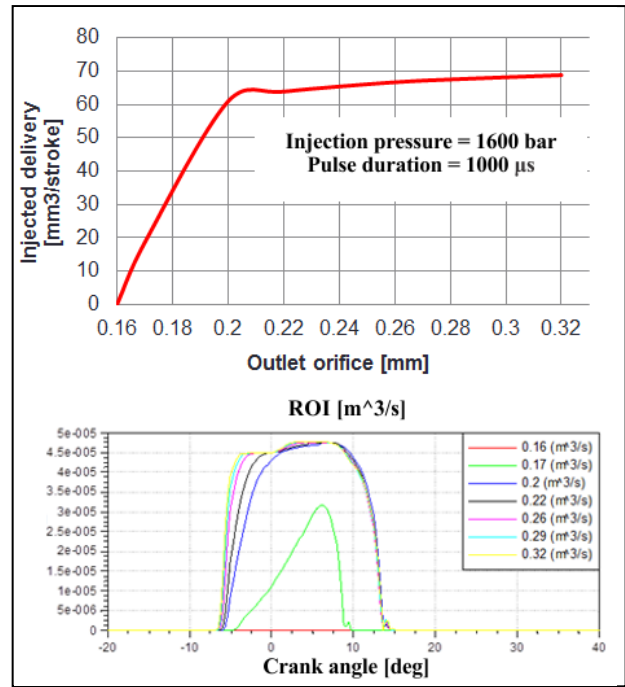
### 5.2 Parametric study on injected delivery

The injector simulation model was used to study influence of several geometric parameters on injected quantity and ROI. Results are presented in Figure 8, 9 and 10. The influence of needle diameter on injection process is presented in Figure 8. Increasing the diameter slightly increases the injected quantity due to the fact that injection duration rises. In this study the diameter was varied from 3.6 mm to 5.3 mm. As a function of increasing diameter the injection duration rises within the range from 16 deg to 24 deg. It causes injected delivery of  $72\text{ mm}^3/\text{st}$  at needle diameter value of 5.3 mm. Also, it was observed variation in the start of injection. Higher diameter causes earlier start of injection. This variation is within the range of 2 deg.

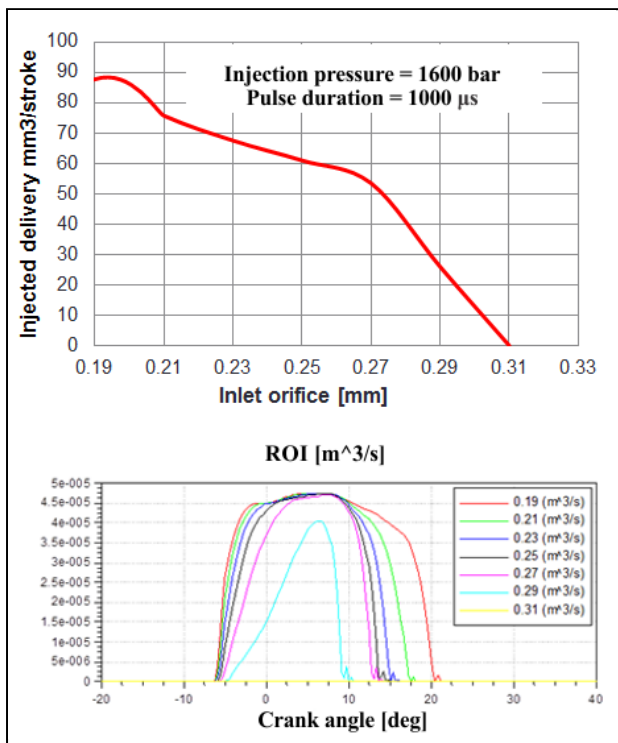




**Figure 8.** Influence of needle diameter on injected delivery and ROI



**Figure 10.** Influence of outlet orifice on injected delivery and ROI



**Figure 9.** Influence of inlet orifice on injected delivery and ROI

Inlet and outlet orifices of control volume are the most important parameters for injection control of solenoid injectors. This fact was confirmed by results presented here. The injected delivery highly depends of inlet orifice as shown in Figure 9. The orifice was varied within the range from 0.19 mm to 0.31 mm. It was observed that higher values decrease rapidly injected

fuel as well as the injection duration. In fact, increasing the size by 0.06 mm than basic diameter (Table 1) causes zero injected delivery.

The influence of outlet orifice is also significant but the function is different. The injected delivery was studied as the orifice diameter was varied within the range of 0.16 mm to 0.32 mm. The value which was used in injector calibration was 0.2 mm. Increasing that value causes small rise of injected fuel which reaches 70 mm<sup>3</sup>/st. However, decreasing the basic values (Table 1) causes significant reduction of injected delivery. It was observed that at diameter value of 0.16 mm the injected fuel is zero.

## 6. Conclusions

A simulation model of solenoid injector of common rail diesel fuel system was proposed. The model was developed by means of advanced simulation code AVL BOOST HydSim. A validation of the model was carried out as simulated fuel quantity per injection was compared with the value measured on a Hartrige test stand. The comparison was conducted at three injection pressure: 400 bar, 800 bar and 1600 bar, and pulse duration within the range of 0 μs to 1600 μs. A small deviation was observed at injection pressure of 400 bar and 800 bar. Higher differences between measured and simulated values were observed at 1600 bar. The maximum deviation of 7.17 mm<sup>3</sup>/st was found at low pulse duration. The model calibration was carried out by variation of several geometric parameters such as control volume, needle volume and nozzle orifice.

By means of numerical simulation ROI was estimated as a function of pulse duration and injection pressure. It was observed that at low injection pulse (400µs) the ROI shape is triangular due to the fact that the needle has not reached the maximum lift. The results also revealed that the injection duration is not a constant value at constant pulse duration and different injection pressure.

A parametric study of various geometric parameters on injection process was finally presented. Three parameters were chosen: needle diameter, inlet orifice and outlet orifice of the control chamber. The results revealed significant influence of both inlet and outlet orifices. The most important is the fact that small variation than base values of the diameters cause injected delivery to be zero.

#### Acknowledgement

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## ИЗСЛЕДВАНЕ НА ХАРАКТЕРИСТИКИТЕ НА ПОДАВАНЕ НА ГОРИВО НА ВПРЪСКВАЧ С ЕЛЕКТРОМАГНИТНО УПРАВЛЕНИЕ ОТ COMMON-RAIL ГОРИВНА СИСТЕМА

ПЛАМЕН ПУНОВ

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#### Резюме:

В публикацията е проведено изследване на впръсквач с електромагнитно управление от дизелова горивна система тип common-rail с цел определяне характеристиките на горивоподаването. Изследваният впръсквач е на фирмата Delphi, като е предназначен за монтиране в дизеловите двигатели с ходов обем 2.0 литра на фирмата PSA. За изследването е разработен симулационен модел на впръсквача с помощта на програмата AVL BOOST HydSim. Геометричните параметри на елементите на впръсквача бяха взети от техническа документация, докато масите на движещите се детайли бяха измерени. За калибриране на модела беше проведено експериментално изследване на впръсквача следвайки процедурата за изпитване на фирмата Delphi. Точността на моделът беше оценена чрез съпоставяне на експерименталните и изчислените стойности на цикловото количество впръснато гориво. С помощта на модела беше изследван закона за подаване на гориво и влиянието на някои геометрични параметри върху количеството на впръснатото гориво.

**Keywords:** електромагнитен впръсквач, common-rail, симулация, експериментално изследване, закон за впръскване