SIMULATING INPUT AND OUTPUT FLOW RATE OF THE CUMMINS INJECTOR

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Abstract: *One of the most common injection system uses an injector-pump for introducing the fuel into the cylinder. The system analyzed in this work, called Cummins, is composed by a low-pressure circuit in which there is a pump that supplies the number of injectors proportional to the number of engine cylinders. Cummins injectors allow the deletion of high pressure tubes and all the problems to do with, although the regulation and the setting up of the system are difficult.*

Keywords: *diesel engine; simulation modeling; Simulink; solenoid valve*

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1. INTRODUCTION

Diesel engines are widely used in transport, including automobile and tractor equipment, railway locomotives, as well as tank building and shipbuilding. Experimental studies in which different parameters are recorded [1–2] are associated with various difficulties, first of all, they require a specialized laboratory. Therefore, at the design stage, the method of simulation is used [3–5], for example, in the Simulink environment.

The quality of spraying diesel fuel in the cylinder, largely determines the process of its combustion, and the formation of toxic substances in the exhaust gases. Better spraying is achieved at high pressures, of the order of 1800 bar and higher [6–13]. However, obsolete diesel engine systems cannot provide fuel to the injectors at this pressure, because in this case it would be necessary to make high-pressure fuel lines. In order not to use these lines, many leading automotive companies began to use (since 1994 in trucks and since 1998 in passenger cars) electronically controlled pump injectors [14–23].

The principal components of the mechanism that have been analyzed are the **plunger**, the **accumulator**, the **injector** and the **solenoid valve**.

2. FUNCTIONING

The Cummins injection system is controlled by a rocker arm, driven by a cam (Fig. 1). At the beginning the plunger is in its top position and the solenoid valve is normally closed, which means that no supply voltage is passing through it and no fuel can pass into the fueling channels. Subsequently, the solenoid is excited by the supply voltage, the core of the solenoid valve 6 moves and acts on the spool 8. The valve opens and the fuel from the make-up pump enters a special chamber 25. When the solenoid is no more excited, the filling of the fuel in the chamber stops.

The cam starts to rotate, and the variable force P that the rocker arm applies on the plunger 3 is assigned, moving it downward more and more. The plunger that is moving to the bottom increases pressure in the cavity 25. A part of flow rate is absorbed by the accumulator and another part passes through a channel that connects the plunger's cavity to the injector cup.

When the pressure is such as to win the strength of the spring 22, the injector needle raises and permits the passage of fuel into small spray holes (0.0002 m). The injection starts and the fuel is well atomized. When fuel is injected into the cylinder, the pressure drops, the control unit gives a signal to open the valve in order to restart the fuel flow to the dedicated chamber and maintain a constant pressure. The injection pressure is approximately 1800 bar.

To stop the fuel injection process, the voltage to the valve coil should be cut off, resulting in the magnetic flux disappearing, as well as the magnetic attraction force, and the spring moves the valve needle to its initial position on the stop.

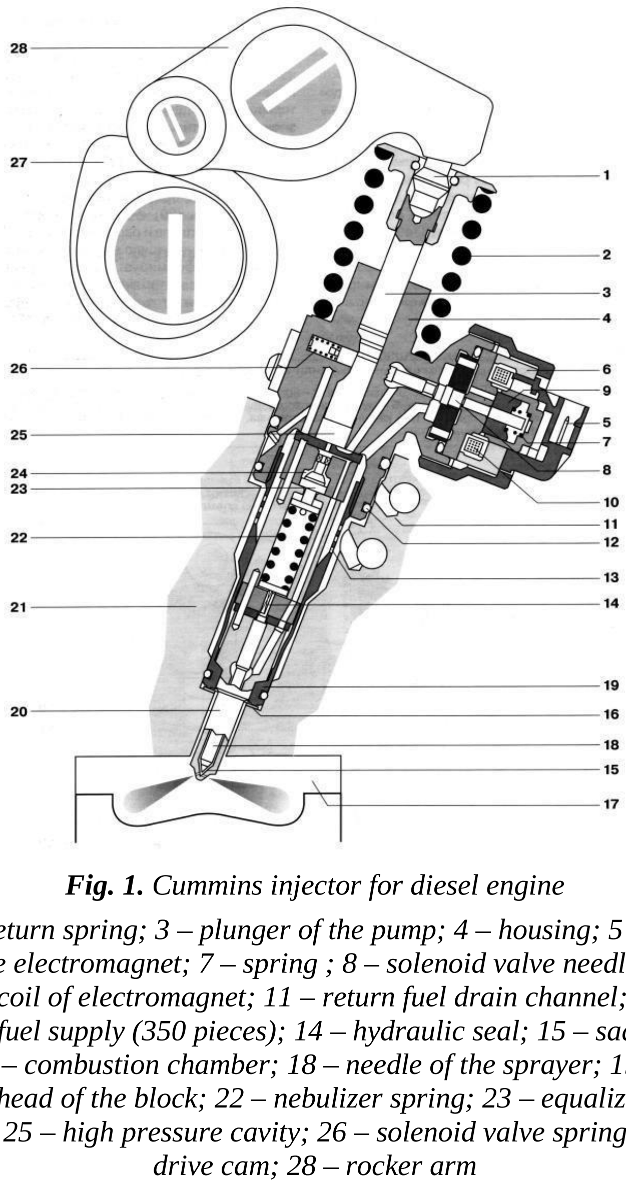

Fig. 1. *Cummins injector for diesel engine*

1 – ball joint; 2 – return spring; 3 – plunger of the pump; 4 – housing; 5 – plug for a control signal; 6 – core of the electromagnet; 7 – spring ; 8 – solenoid valve needle; 9 – armature of the electromagnet; 10 – coil of electromagnet; 11 – return fuel drain channel; 12 – compaction; 13 – openings-filters of fuel supply (350 pieces); 14 – hydraulic seal; 15 – saddle of a needle; 16 – sealing washer; 17 – combustion chamber; 18 – needle of the sprayer; 19 – spray nuts; 20 – nebulizer; 21 – the head of the block; 22 – nebulizer spring; 23 – equalizing piston; 24 – fuel accumulator cavity; 25 – high pressure cavity; 26 – solenoid valve spring; 27 – pump-injector drive cam; 28 – rocker arm

3. SIMULATION

The method for calculating the working process of fuel equipment is based on the "theory of unsteady flow of a real liquid in a fuel line. It is assumed that the movement of the fuel is one-dimensional and isothermal, and its density and velocity of propagation of the pressure pulse are constant" [24]. Simulink was used to calculate the flow rate and pressure at the outlet of the atomizer. In fig. 2 shows the general block diagram of the simulation, which consists of three main parts:

1) input parameters;

2) injector-pump;

3) electrical fuel supplier.

The simulation aims to take into account the construction and working parameters of the injector-pump in order to estimate:

1) injector flow rate;

2) fuel consumption through solenoid valve.

The simulation can then be used to tune every single parameter in order to match the two parts.

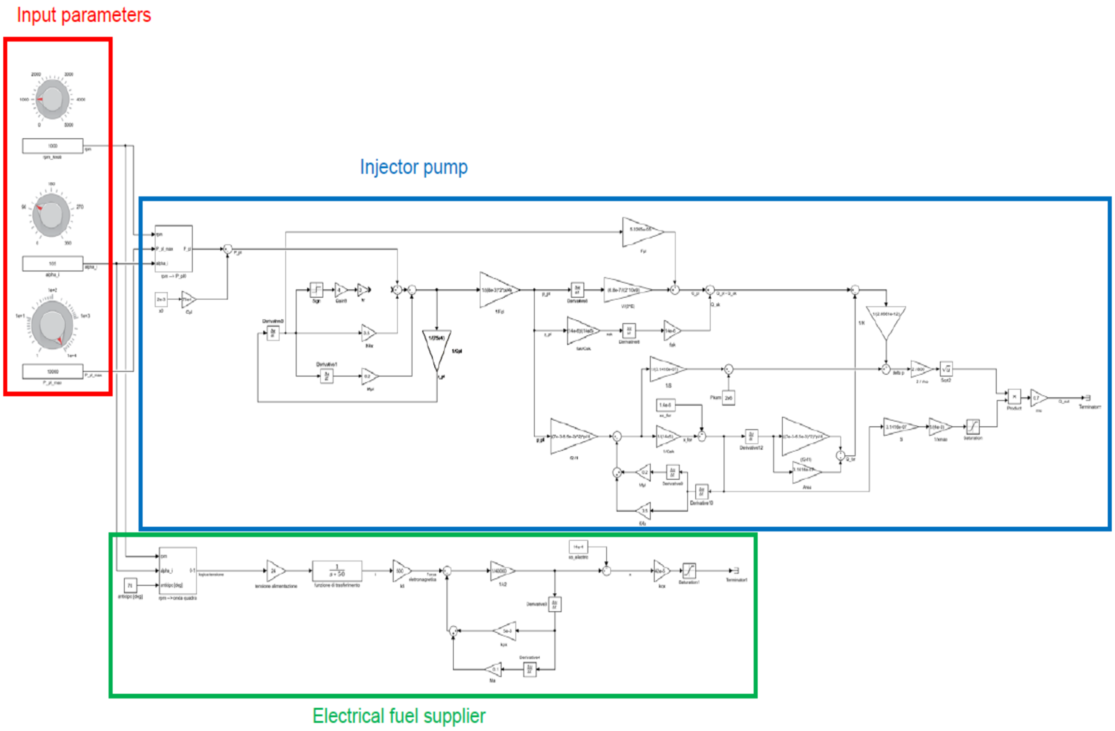

***Fig. 2.** Simulation general overview*

4. INPUT PARAMETERS

The outside inputs that don't depend upon the injector pump are (Fig. 3):

• rotation velocity (rpm_knob);

• cam's force peak (P_pl_max);

• cam amplitude and angle (alpha_i).

By changing these parameters, you can obtain different values of flow rates. The chosen input values are:

• rotation velocity = 1000 rpm;

• P_pl_max = 10000 N;

• alpha_i = 105°.

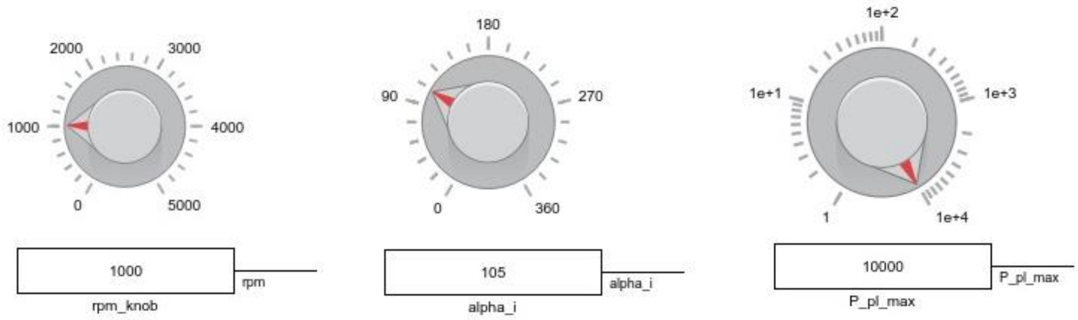

Fig. 3. *Input parameters*

5. INJECTOR PUMP

Mathematical model of the injector pump consists of the following equations. Forces acting on plunger:

$$P - C_{пл}\left(x_0 + x_{пл}\right) = M_{пл}\ddot{x}_{пл} + k_{4x}\frac{dx_{пл}}{dt} + f_{тр}\mathrm{sign}\frac{dx_{пл}}{dt} + P_{пл}F_{пл}$$

Equation of the injector flow rate:

$$Q_ф = F_{пл}\frac{dx_{пл}}{dt} + \frac{V}{2E}\cdot\frac{dp}{dt} - Q_{ак} - \left[\frac{\pi\left(d_2^2 - d_1^2\right)}{4} + \frac{\pi d_1^2}{4}\right]\cdot\frac{dx_ф}{dt}.$$

Equation of the sprayer flow rate:

$$Q_ф = \mu\pi S_1\sqrt{\frac{2\Delta p}{\rho}}.$$

Equation of the accumulator:

$$P_{пл}f_{ак} = C_{ак}x_{ак}.$$

Equations of the injector:

$$M_3\ddot{x}_ф = P_{пл}\frac{\pi\left(d_2^2 - d_1^2\right)}{4} - C_{ак}x_{ак} - k_{4x}\frac{dx_ф}{dt} - f_{тр}\mathrm{sign}\frac{dx_ф}{dt};$$

$$Q = K \cdot \Delta p .$$

The required number of holes will participate depending on the degree of the nozzle needle lift. Therefore, the area of diesel fuel supply can be expressed by the following relationship:

$$f_{\phi} = S_1 \frac{x_{\phi}}{x_{max}} n ,$$

where S_1 is the area of one hole;

x_{max} – the maximum stroke of the nozzle needle.

Given constant parameters are present in the Table 1.

Table 1. *Parameters of the injector pump*

Parameter	Abbrev.	Meaning
Base area of the plunger	$F_{пл}$	$5{,}03 \cdot 10^{-5}$ m^2
Preload of the spring	x_0	$2 \cdot 10^{-3}$ m
Return spring stiffness	$C_{пл}$	750000 N/m
Displacement of the plunger	$x_{пл}$	$6 \cdot 10^{-3}$ m
Mass of the plunger	$M_{пл}$	0,2 kg
Coefficient of viscous friction	k_{4x}	4,5 N·s/m
Friction force	$f_{тр}$	3 N
Number of spray holes	n	10
Area of one spray hole	S_1	$3{,}14 \cdot 10^{-8}$ m^{-2}
Biggest injector needle diameter	d_2	$7 \cdot 10^{-3}$ m
Smallest injector needle diameter	d_1	$6{,}5 \cdot 10^{-3}$ m
Mass of the injector needle	M_3	0,1 kg
Base area of the accumulator	$f_{ак}$	$14 \cdot 10^{-6}$ m^2
Accumulator spring	$C_{ак}$	1400000 N/m
Volume of the accumulator	V	$6{,}8 \cdot 10^{-7}$ m^3
Diameter of the plunger	$d_{пл}$	$8 \cdot 10^{-3}$ m
Coefficient of flow rate	μ	0,7
Bulk modulus	E	10^9
Area of one hole	S_1	$3{,}14 \cdot 10^{-7}$ m^2
Pressure in the cavity	P_{kam}	$2 \cdot 10^6$ Pa
Maximum displacement of the injector	x_{max}	$4 \cdot 10^{-3}$ m
A constant	K	$2{,}8661 \cdot 10^{-12}$ m^4·s/kg
Density of the fuel	ρ	800 kg/m^3

Variables used in these equations are as follows:

$P_{пл}$ – pressure of the plunger, Pa;

P – force applied by the cam, N;

Q_{ϕ} – injector flow rate, m^3/s;

x_{ϕ} – injector displacement, m;

$Q_{ак}$ – accumulator flow rate, m^3/s;

$x_{ак}$ – accumulator displacement, m.

In fig. 4 shows a block diagram of an injector pump simulating the above equations. In particular, you can notice the block that models the cam's law which drives the plunger.

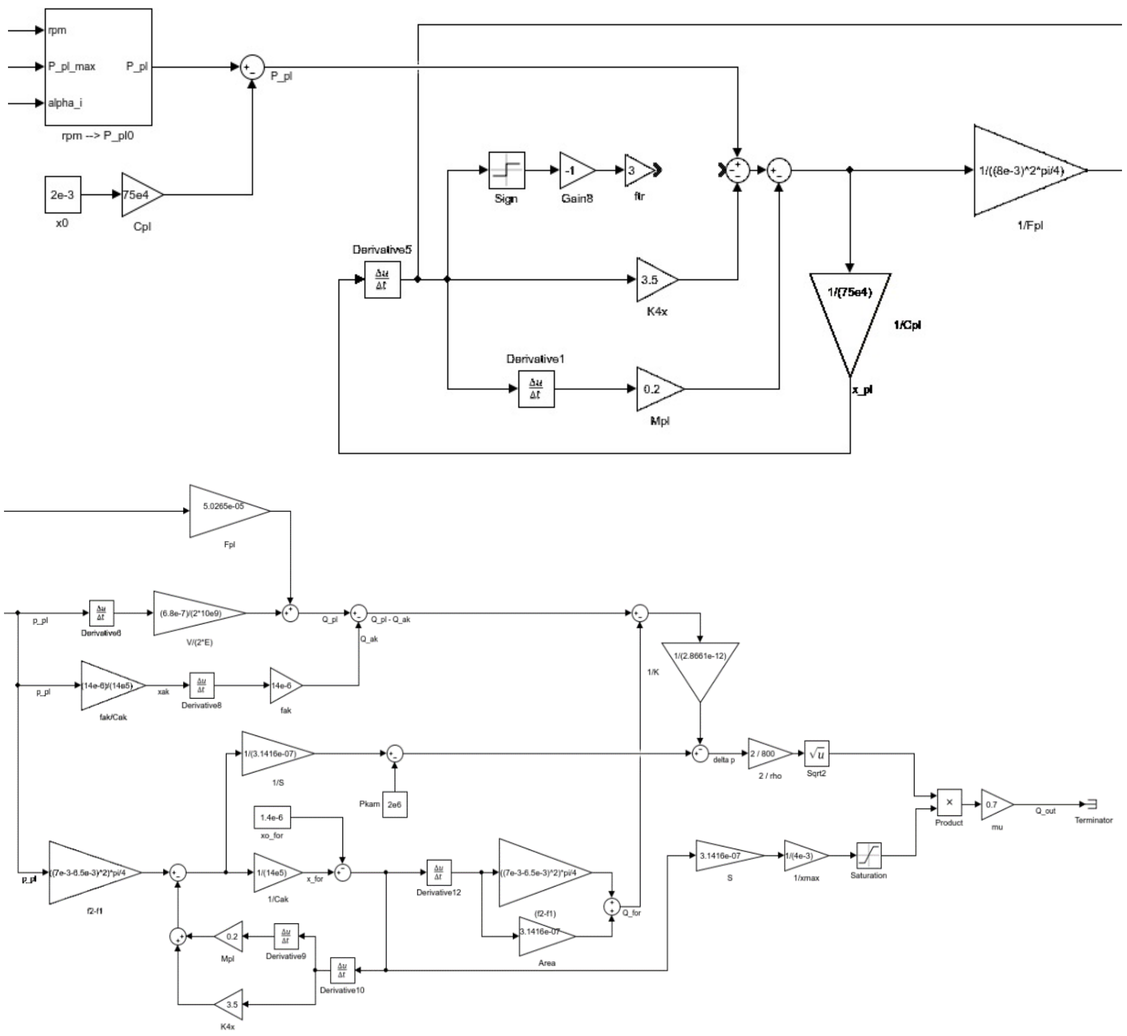

Fig. 4. *Injector pump block in Simulink*

The cam law is described by a fourth order polynomial $a+bx+cx^2+dx^3+ex^4$ and it has been derived trough the block shown in Fig. 5, knowing in advance the trend of the cam force as a function of the rotation angle. The law of the cam has been created starting from the polynomial function between $0–\pi$ and mirroring the curve between $\pi–2\pi$.

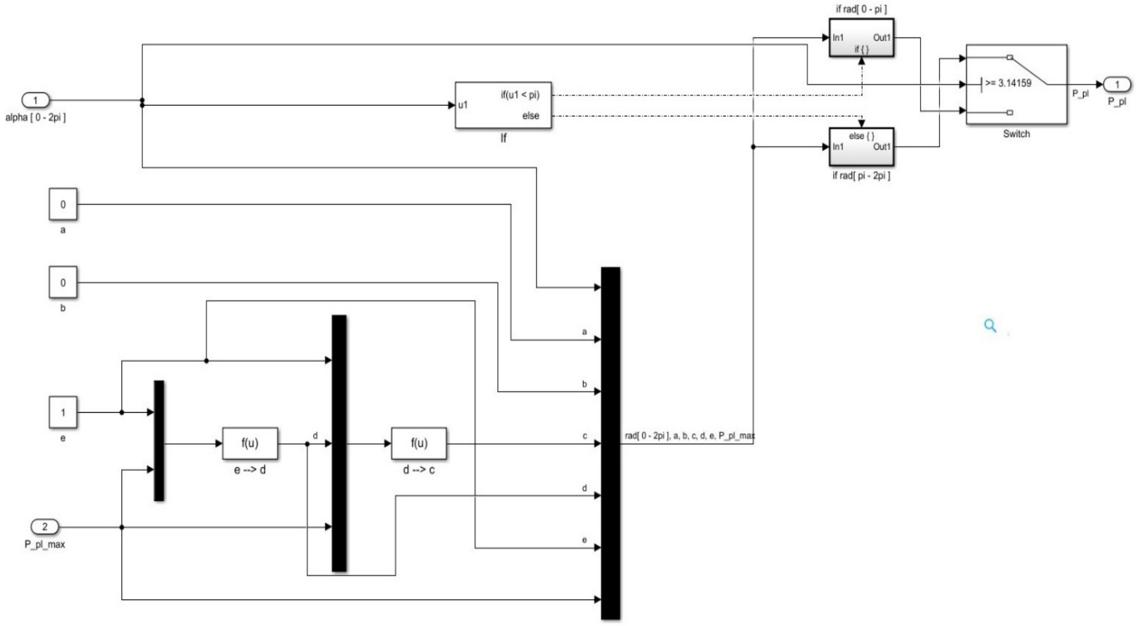

Fig. 5. *Block diagram of the movement of the cam*

After having created the curve from the polynomial function, it's in the following block (Fig. 6) that the process of changing the force created by the cam on the plunger is constructed. In fact, here it has been imposed that between an angle 0° and alpha_i=105° the value of the force applied on the plunger is null, while between an angle alpha_i=105 and 2π, it has been used the curve previously obtained from the polynomial function. Furthermore, by adding the constant force P_pl_sosta, we take into account the preload that is used to prevent the cam from being removed from the tappet. The curve of the cam force is shown in Fig. 7.

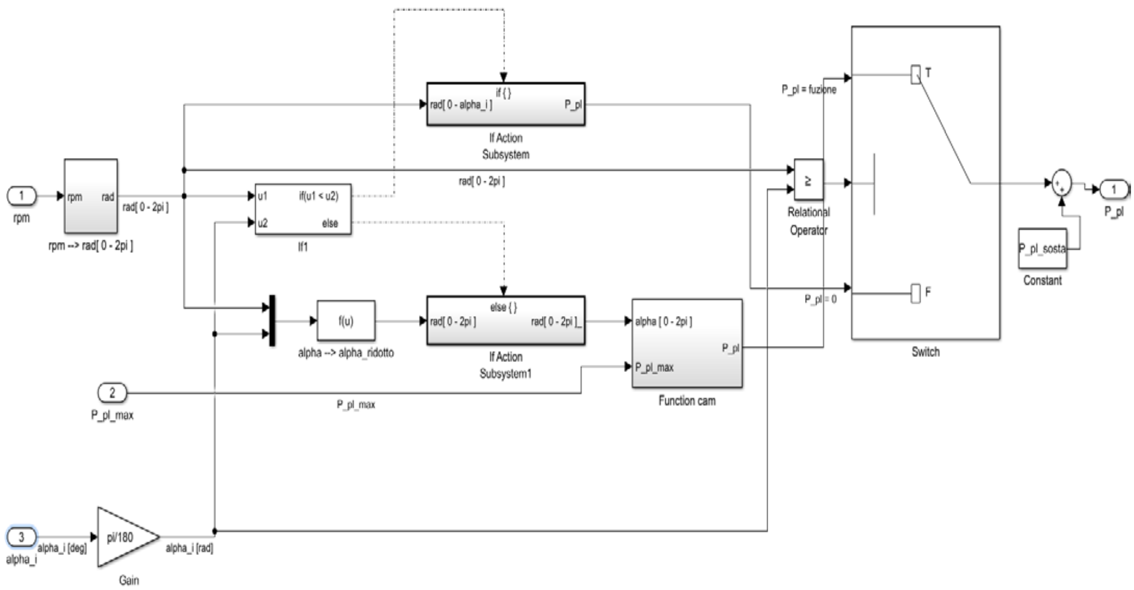

Fig. 6. *Block in which is calculated the cam force*

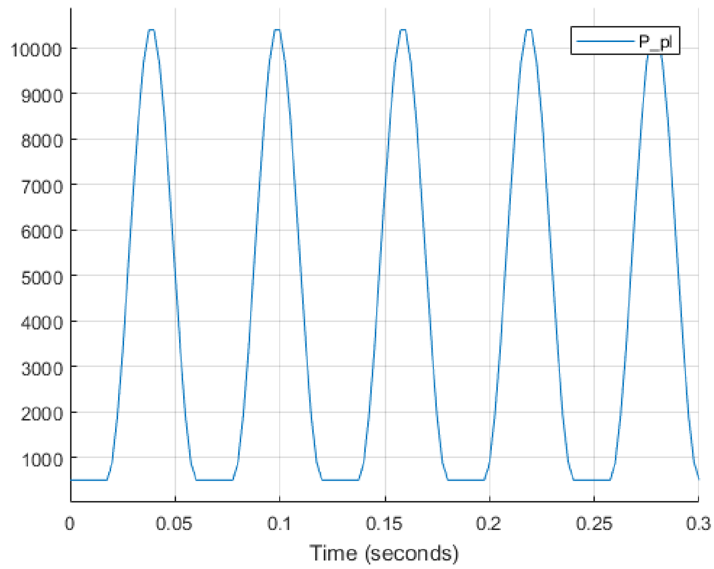

Fig. 7. *Cam force P_pl*

After calculating the force generated on the cam, we use the first equation related to the plunger with the purpose to obtain the pressure in the plunger chamber (Fig. 8), the curve of which is shown in Fig. 9.

$$P_{пл} = \frac{P - C_{пл}\left(x_0 + x_{пл}\right) - \left(M_{пл}\ddot{x}_{пл} + k_{4x}\frac{dx_{пл}}{dt} + f_{тр}\text{sign}\frac{dx_{пл}}{dt}\right)}{F_{пл}}.$$

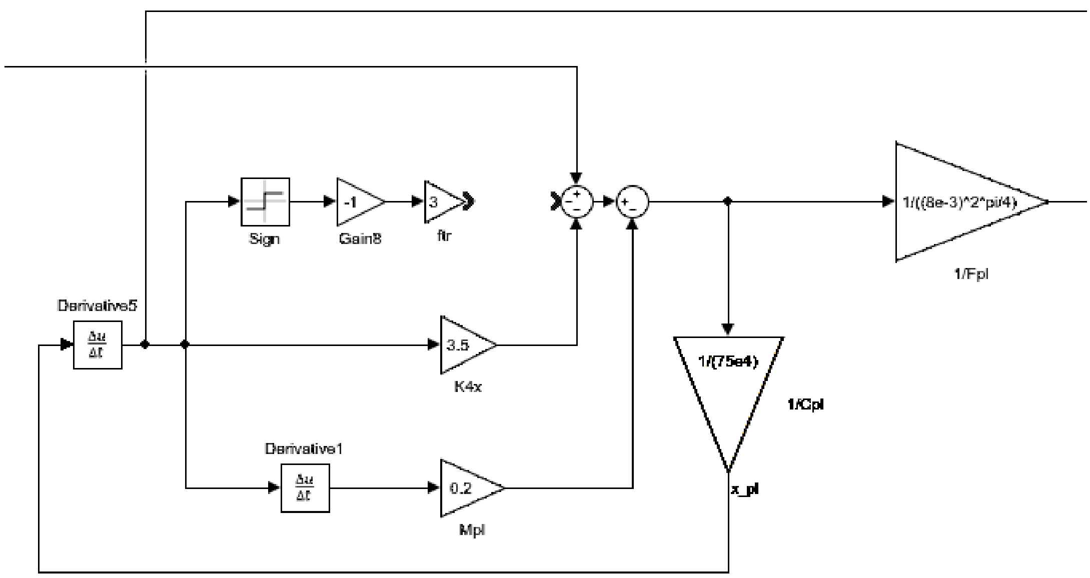

Fig. 8. *Block diagram for calculating the movement of the plunger*

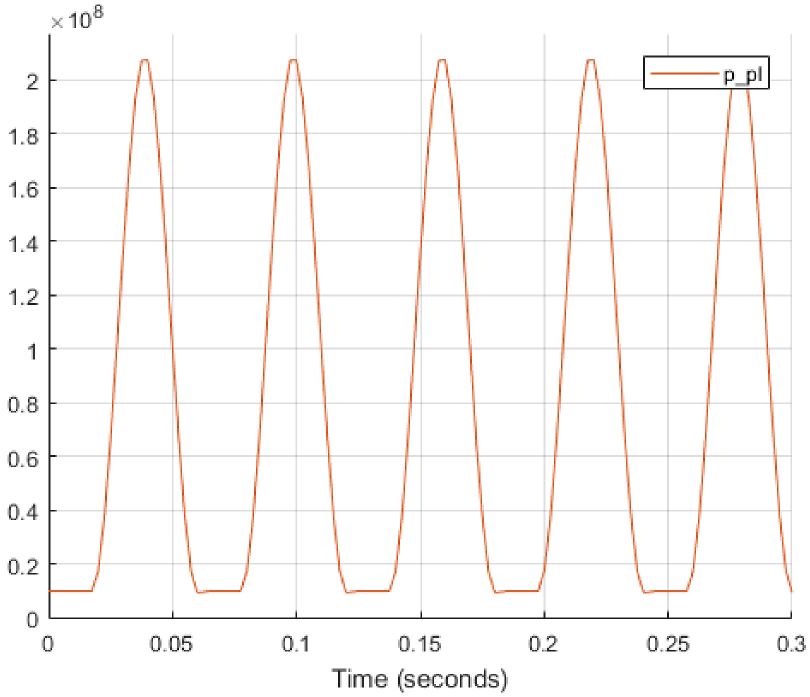

Fig. 9. *Pressure in the plunger's chamber*

Due to the feedback it is possible to know the value of the plunger movement and therefore of the pressure. Now it's possible to continue with the other equations and calculate the following parameters. This equation permits to know the displacement of the accumulator piston:

$$x_{ак} = \frac{P_{пл} f_{ак}}{C_{ак}}.$$

If the displacement of the accumulator is known, it's possible to calculate the flow rate of this one, thanks to this equation:

$$Q_{ак} = f_{ак} \frac{dx_{ак}}{dt}.$$

The flow created by the plunger can be calculated according to the structural diagram shown in Fig. 10:

$$Q_{пл} = F_{пл} \frac{dx_{пл}}{dt} + \frac{V}{2E} \cdot \frac{dp}{dt}.$$

The curve of the flow rate out of the injector is shown in Fig. 11.

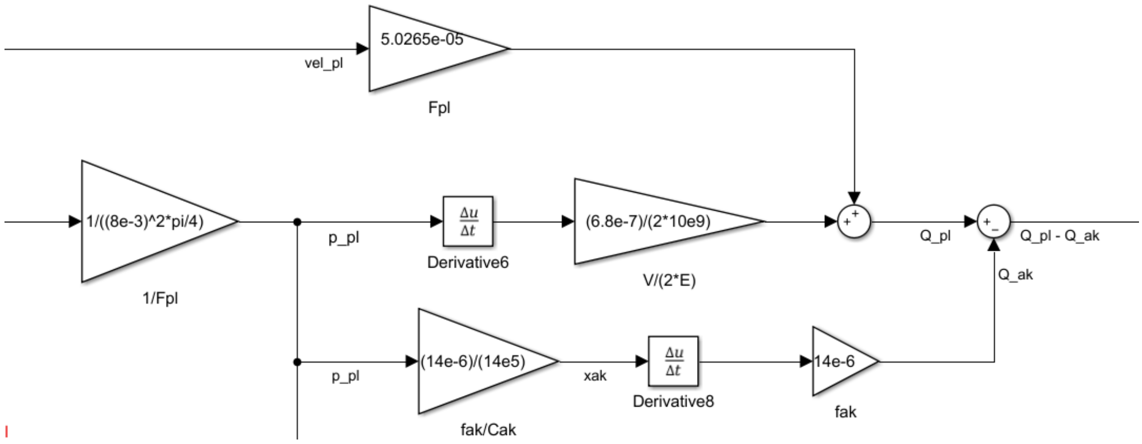

Fig. 10. *Block in which is calculated the flow rate out of the injector*

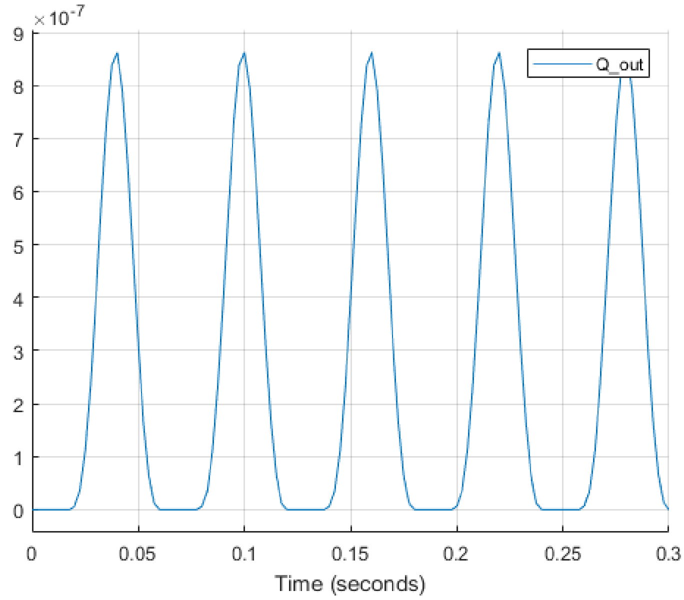

Fig. 11. *Flow rate out of the injector*

6. ELECTRIC FUEL SUPPLIER

In order to estimate the flow rate that goes out of the electric unit, three more equations are needed:

$$\Delta u = iR + L\frac{di}{dt};$$

$$M\ddot{x} = K_{fi}i - F_{tp} - K_{px}\frac{dx}{dt} - c\left(x + x_{02}\right);$$

$$K_{qx}x - K_{qp}\cdot\Delta P = f_{пл}\frac{dx_{пл}}{dt} + \frac{V}{2E}\cdot\frac{dp}{dt},$$

where i – amperage, A;

x – displacement of the solenoid valve spool, m.

Given constant parameters are present in the Table 2.

Table 2. *Parameters of the electric fuel supplier*

Parameter	Abbrev.	Meaning
A coefficient	K_{qx}	$42 \cdot 10^{-5}$ m²/s
A coefficient	K_{qp}	$12 \cdot 10^{-11}$ $m^4 \cdot s/kg$
Pressure drop allowing fuel to flow from the electrical block to the compression chamber of the plunger	ΔP	$1{,}6 \cdot 10^{6}$ Pa
Viscous friction	K_{px}	0,005
Mass of the spool	M	0,1 kg
Coil inductance	L	3 H
Spring stiffness	c	40000 N/m
Preload of the spring	x_{02}	$5 \cdot 10^{-3}$ m
Coil resistance	R	50 Ohm
A constant	K_{fi}	500 H/A
Friction force	F_{tp}	0

The parameters of the whole systems have been matched (Fig. 12) so that the electrical fuel supplier let the fuel enter in the injector-pump when the plunger is moving up.

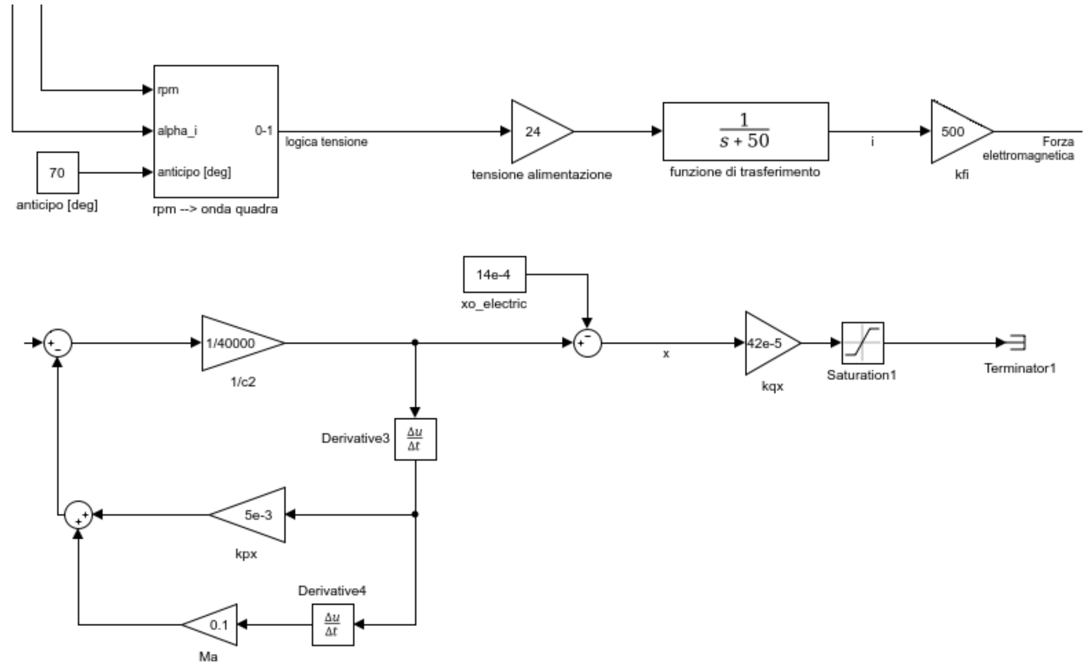

Fig. 12. *Block in which parameters of the whole systems are matched*

7. CONCLUSION

You can see in fig. 13 that the fuel supply solenoid valve provides a periodic flow similar to the flow generated by the plunger, but in antiphase. When the plunger piston compresses fuel, the solenoid valve closes.

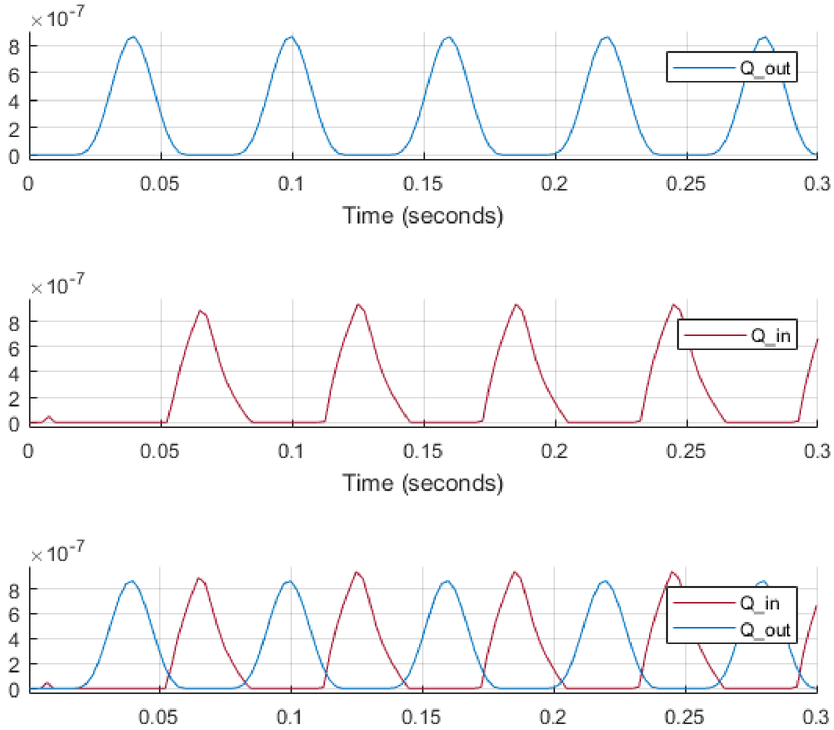

Fig. 13. *Comparison between the flow rate which enters (Q_in) and exits (Q_out) the plunger chamber*

Thus, the proposed simulation model allows to estimate flow rate of the Cummins injector and its solenoid valve.

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