DEVELOPMENT OF 1D SIMULATION MODEL OF FUEL INJECTOR FOR PFI APPLICATION

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ABSTRACT

Port fuel injection (PFI) engines play a key role in Brazil widely used as power source of the majority car passengers on the market. Selection criteria of fuel injectors used for PFI application is based on injector Dynamic Flow Range (DFR) which means ratio of the maximum to minimum dynamic flows, i.e., the usable minimum and maximum fuel flow. Evaluation of DFR relies usually on measurements on test benches using constructed samples. This paper presents the development process of 1D simulation model of fuel injector for PFI application built on AMESim® software. This functional model integrates magnetic, mechanical and hydraulic domains and it aims to assist selection and specification of proper fuel injector to fulfill application requirement establishing a better first-time product capability reducing samples construction. Results show a good correlation with real prototypes.

INTRODUCTION

Port fuel injection is Brazilian´s most widely used system for internal combustion engines. In this system the air-fuel mixture is prepared in the intake manifold and fed into the combustion chamber by fuel injectors. The shape of the fuel spray is determined individually for each engine by the position of the injector and the configuration and number of orifices. Various injector variants with different design parameters combination and spray patterns fulfill a broad variety of requirements including operational pressure, flow rates and DFR.

Over the last years, the use of simulation during product development has been extended to several domains especially to system simulation also known as 1D Simulation. On this kind of simulation, the model behavior is only function of time and single axis dimension, not requiring precise 3D geometry. A full schematic system model is obtained based on analytic modeling of magnetic, mechanical and hydraulic blocks, which are connected following principle of Bond graph theory [1]. This allows assessment of designs and understanding of cause-effect relationships over whole development phases even when design has rough level of details before real sample creation.

This paper will discuss the approach and procedures taken to develop a 1D simulation model of fuel injector for PFI application built on AMESim® software, a powerful tool used for system simulation. The main goal of this simulation model is to give application engineer the ability to quickly evaluate product variants and select fuel injector model that best fulfills customer requirements during quotation phase.

1. PRODUCT DESCRIPTION

1.1. COMPONENTS AND FUNCTIONS

In intake manifold injection, fuel injectors have an important function to ensure the operation of the engine. Essentially, mixture-formation components must ensure that the air/fuel mixture is formed properly for a particular system.

The main tasks of fuel injector are delivery exact fuel amount, at exact timing, according to exact engine moment demand, fuel pulverization before engine intake valve (fuel mixture preparation) and sealing the system when not operated. Another important task of fuel injector is to form the spray shape, spray angle and fuel droplet size, which influences the formation of air/fuel mixture. Figure 1 shows the main components of low pressure fuel injector.

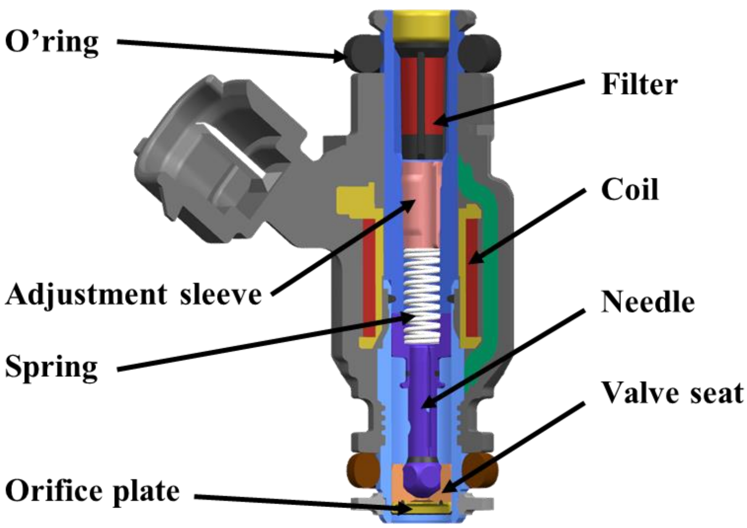

Figure 1 - Components of fuel injector

A filter strainer in fuel injector inlet protects the other components of the injector against contamination. Two O'rings seal the fuel injector form the fuel distribution pipe and the intake manifold. When the coil is de-energized, the spring and force resulting from the fuel pressure presses the valve needle against the valve seat to seal the fuel-supply system from the intake manifold [2].

The fuel injector is energized through the ECU signal and due to this, the coil generates a magnetic field (B) and therefore a magnetic flux (ϕ) which pulls in the armature and lifts the needle of the valve seat. This movement allow the fuel to flow through the fuel injector. In a simplification, magnetic flux can be expressed analytically for equation 1 [3].

$$\phi = \int_S B.da \qquad (1)$$

Where ϕ is the magnetic flux, B is the magnetic field and da is the infinitesimal area element.

The move imminence state of the needle occur when we have an equilibrium forces, expressed for equation 2.

$$Fmag = Fhid + Fs + Fl \qquad (2)$$

Where $Fmag$ is the magnetic force, $Fhid$ is the hydraulic force, provoked by the action of fuel, Fs is the spring force and Fl are the sum of loses forces, provoked by friction.

The injected volume of fuel per time unit is essentially determined by the system pressure and the available cross section of the spray orifices in the orifices plate. The valve needle closes again when the excitation current is switched off [2].
Figure 2 gives a general overview about how the fuel injector works.

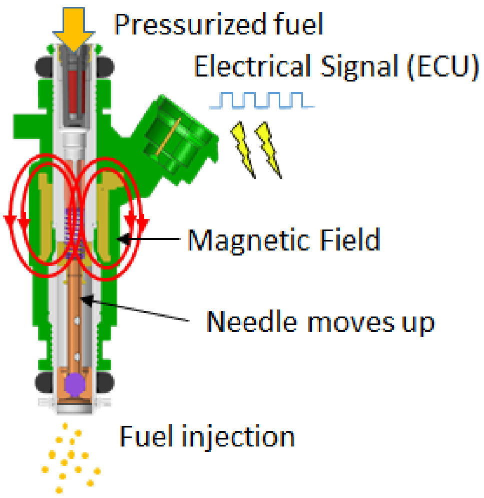

Figure 2 – Work principle of a fuel injector

ECU component sends an electrical signal in pulse format for the fuel injector. According to the engine demand, ECU calculated what period (P) and time of injection (Tinj) are necessary. Period is the time in msec. for the engine complete 1 cycle (intake, compression, ignition and exhaust) and time of injection, refers the time in msec, that the fuel injector valve should be open for the passage of fuel flow. Time of injection is also known as pulse width. Electrical signal received for fuel injector is shown in figure 3.

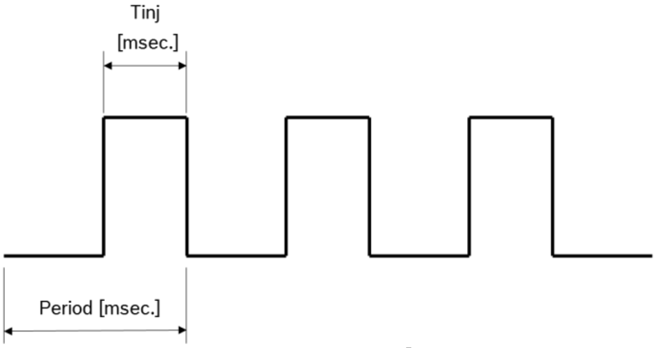

Figure 3 - ECU signal

The measured fuel delivered per pulse of the injector (mg/pulse) when energized at a specified pulse width is known as Dynamic Flow (Qdyn).

1.1. MEASUREMENT OF DYNAMIC FLOW RANGE (DFR)

Measurements on test benches to evaluate characteristics and performance of low pressure fuel injector are done according to SAE recommended practice J1832. Figure 4 shows an example of test bench used for flow measurement.

Figure 4 – Test bench to measure fuel injector flow

Below are listed among others some controlled test parameters:

- Test fluid: Nomal Heptane
- Fluid temperature: measured at the injector inlet and stabilized at 21°C ± 2 °C
- Injector temperature: stabilized at 21°C ± 2 °C
- Pressure: differential pressure across the injection determined by the application and held to within ± 0,5% of this value throughout the test. For this particular work there is an application range from 300 kPA to 450 kpa
- Period: the time elapsed between the beginning of one injection pulse to the beginning of the next pulse: 10 ms ± 0.001 ms

One key characteristic measurement of each injector is the linearity. It represents the possible flow range in which the flow can be expect almost linear to the valve-opening period. Figure 5 illustrates the behavior of flow rate versus injection time. Q_{min} and q_{max} are respectively the minimum and maximum flow rate to keep the linearity at the corresponding time (t_{min}, t_{max}).

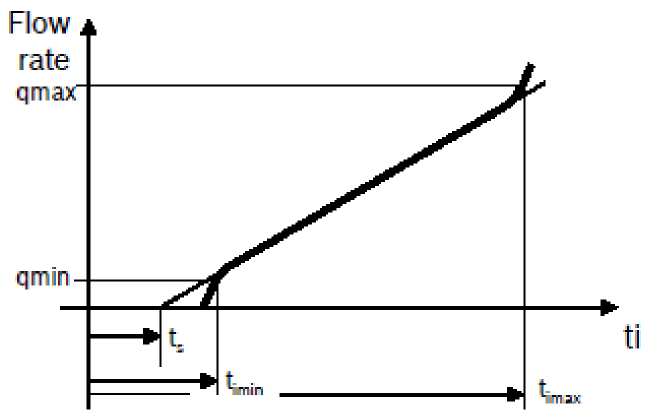

Figure 5 –Flow rate versus injection time – linear range

Dynamic Flow Range (DFR) is one the linearity that defines the individual linearity of each injector. It is calculated as follow:

$$DFR = \frac{q_{max}}{q_{min}} \quad (3)$$

There are some standard methods to calculate DFR. The one used for this work was the SAE Method, where the ideal linearity line (regression line) is defined based on measured data of flow rate at injection time 3, 4, 5, 6 and 7 ms. The deviation between regression line and real measured data is then calculated in percent. The t_{min} and t_{max} are searched so that the actual deviation (delta) from the regression line comes to the specific acceptable value in percent. In this work, the highest acceptable deviation was 5%. Once t_{min} and t_{max} is identified, the reflected q_{min} and q_{max} on the ideal line is obtained and DFR is then calculated.

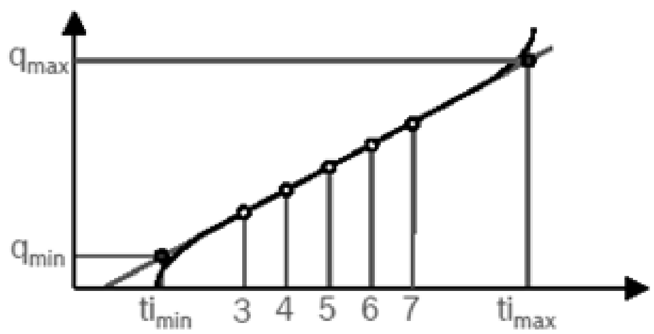

Figure 6 – Flow rate curve with points used for DFR calculation (SAE Method)

2. SIMULATION MODEL METHODOLOGY

Development of 1D simulation model aimed to obtain outputs comparable to measurements on test bench to assist application engineers to evaluate quickly the cause-effect influences of design parameters over fuel injector performance.

Taking as starting point the so-called black box principle, the fuel injector was sub-divided into three functional groups, i.e. electric (magnetic), mechanic and hydraulic. For each block, all relevant inputs and outputs and its relation among blocks were identified as illustrated in Figure 7.

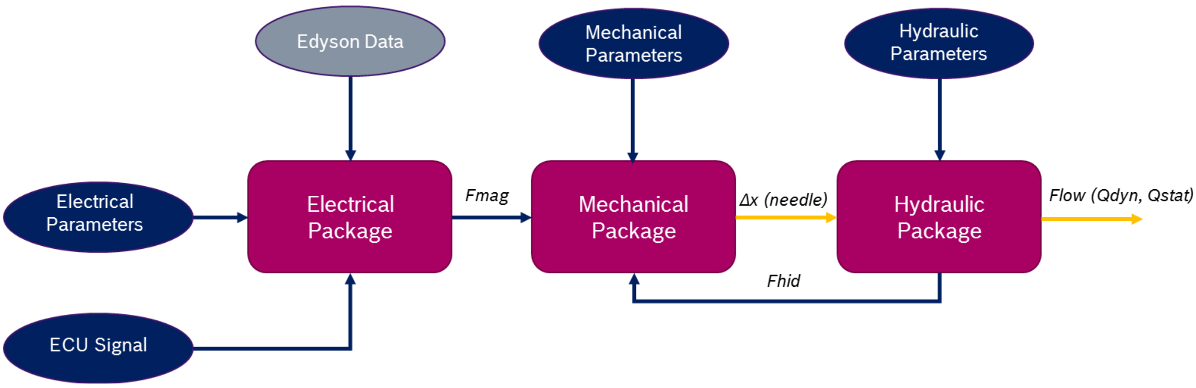

Figure 7 – General view of funcional packages with inputs and outputs

Using a company's in house tool called Edyson it was simulated the steady-state magnetic force (final state). This force serves an input to electrical package, which calculates the magnetic flux based on equation 4 [4] and the electrical parameters.

$$\Phi(t) = U\frac{N}{Rt.\mathcal{R}}(1 - \in^{\frac{-Rt.\mathcal{R}}{N^2}.t}) \qquad (4)$$

Where:
Φ = Magnetic flux [Weber]
N= number of turns [-];
Rt= Circuit resistance [Ω];
$\mathcal{R}$= Circuit magnetic reluctance [1/H]
U= Voltage [V]
T= time [s]

Electrical package then uses the magnetic flux and the steady-state magnetic force to calculate the transient magnetic (F_{mag}) force, which is used as input to mechanical package.

Mechanical package represents the spring force and loses forces of which are calculate through the input of mechanical parameters (see Table 1) using AMESim® standard blocks.

Hydraulic package compute the *Fhid* and flow through the hydraulic parameters using AMESim® standard library and Bosch library.

The packages interact among them as shown in figure 7. The magnetic force is the input to the mechanical package. In the same time, spring force and loses force are calculated on the mechanical package and parallel of this, hydraulic force is compute on hydraulic package and returns to the mechanical package. On the mechanical package, the resultant force is compute. When the forces are not in equilibrium, the needle starts to move. The displacement of the needle allows the passage of fuel flow, which is calculated by the hydraulic package.

Table 1 and 2 show the main inputs parameters and outputs of each functional package

Table 1: Input parameters of simulation model with values range (min. – max.)

Electrical parameters	Voltage [V]	6 - 14
	Indutance [mH]	9 - 17
	Resistance [Ω]	10 - 14
	Number of turns [-]	300 - 400
Mechanical parameters	Needle mass [g]	1.0 - 1.5
	Coeficients of friction [-]	-
	Spring stiffness [N/m]	50 - 70
	Spring Load [N]	2 - 8
	Damper rating [N/(m/s)]	10 - 100
	Max. Needle displacment [μm]	50 - 100
Hydraulic parameters	Needle length [mm]	8.0 - 18.5
	Diam.fuel injector intake [mm]	2 - 5
	Diam. off ball [mm]	3.0 - 4.0
	Diam. of needle holes [mm]	1 - 2,5
	Fuel type [-]	N-heptan; E10 - E100
	Pressure drop orifice plate [cm³/min @kPa]	200 - 400 @300kPa
	Pressure operation [kPa]	350 - 450
ECU Signal	Period [ms]	10
	Tinj [ms]	1.0 - 9.9

Table 2: Main outputs parameters available on simulation model

Electrical package	Magnetic Force [N]
Mechanical package	Needle displacement [μm]
Hydraulic pakage	Flow [L/h]
	Qdyn [mg/pulse]

As mentioned above, the complete model was created on AMESim® software, using both standard components and blocks as well Bosch's library components. Figure 8 gives an overview of the simulation model and how several blocks are connected.

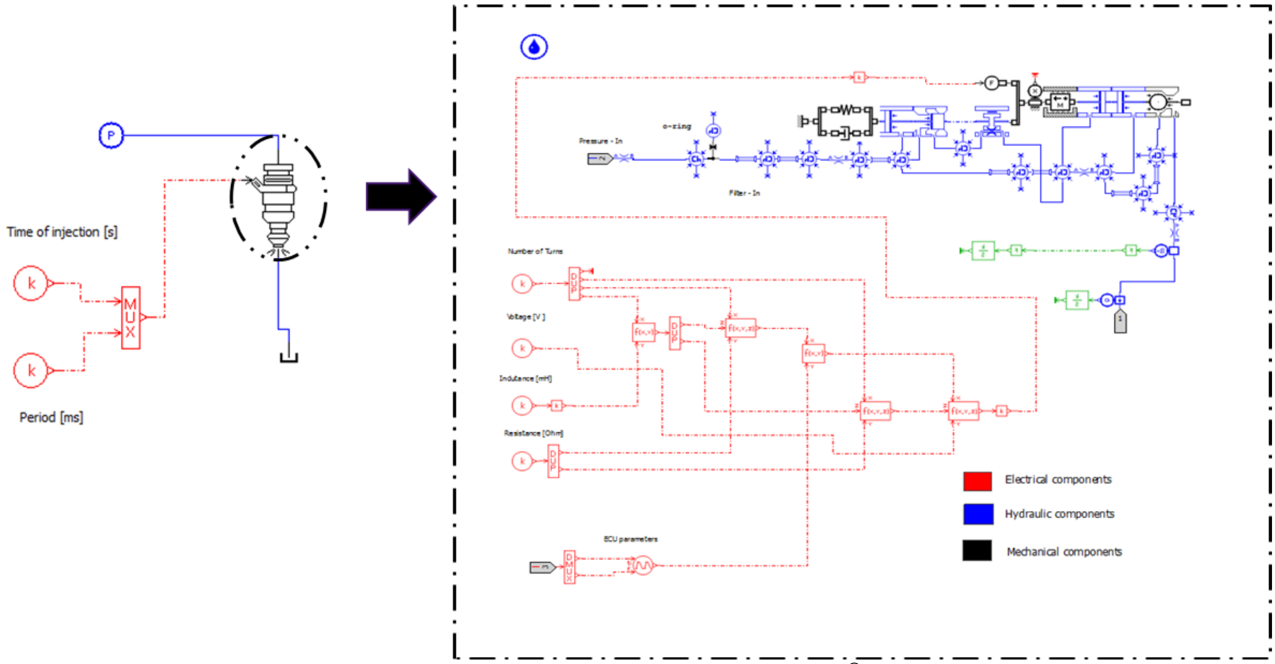

Figure 8 - General view of Fuel Injector AMESim® model

3. RESULTS

Simulation results showed in this section follow the principals of SAE J1832. Fuel used for simulation was N-Heptan and the period was set to 10 msec. Qdyn is the accumulated flow injected in each pulse. Figure 9 shows as illustration for Tinj. 3 to 7 msec the accumulation of mass flow per pulse and for each injection time. It is possible to observe in this figure that the fuel injector have 10 pulses. The average Qdyn is obtained taking the accumulate flow dividing it by the number of pulses. Figure 10 shows the average Qdyn per injection time.

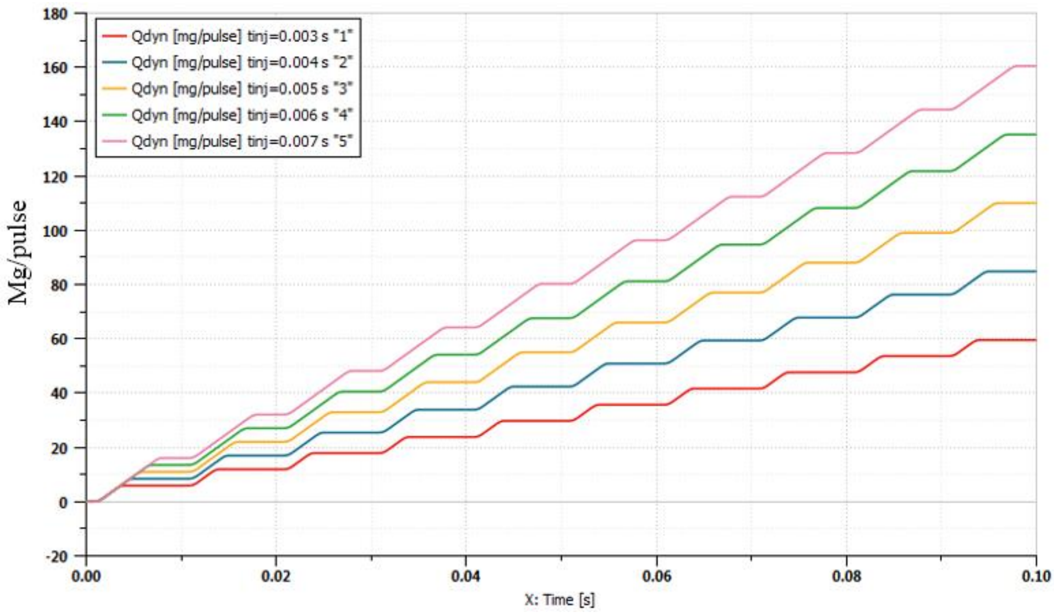

Figure 9 - Accumulated flow by the time

From figure below it can be seen a good correlation between simulation and measurements.

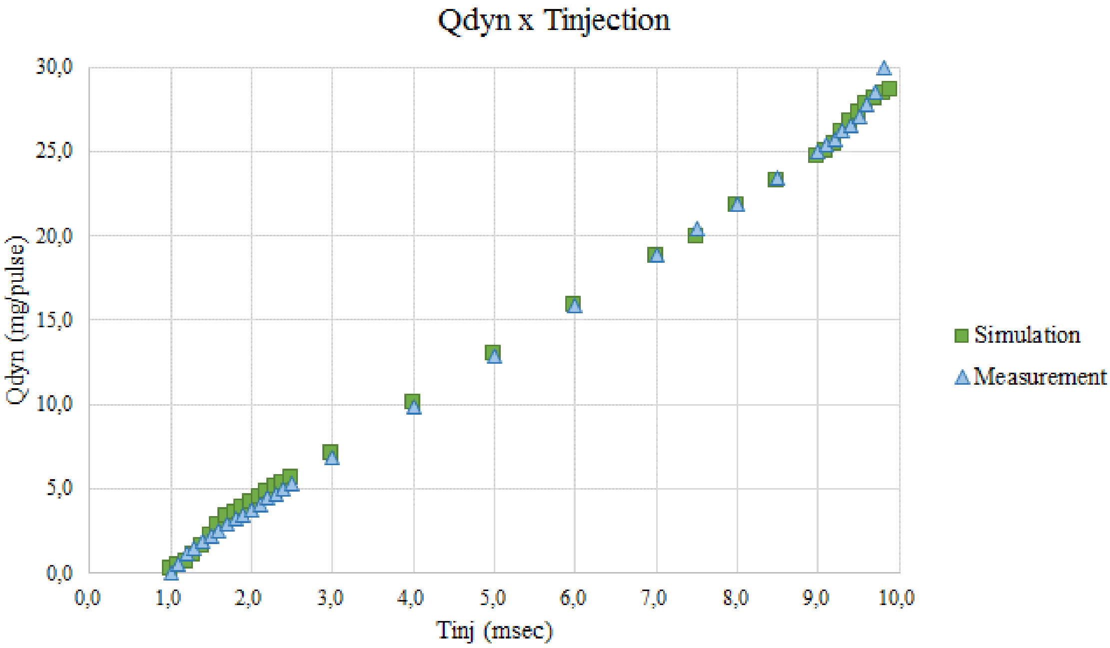

Figure 10 - Comparison between simulation and measurement

As described on section 1.1 the injection time range from 3 to 7 msec. has an important meaning once it is used for DFR calculation. This calculation relies on a reflected q_{min} and q_{max} on the ideal line regression line as per SAE recommended practice J1832. Table 4 shows the results and corresponding error level obtained by this method.

Comparison of simulation results was carried out with results of 12 samples measurements. The deviation between simulation model and real measurements was accounted with average value of whole samples. However, variation of sample characteristics such as spring force, needle displacement, geometries, electrical resistance, etc. led to measurements dispersal. A stochastic simulation e.g. Monte Carlo, is recommended to be performed to consider variation of simulation parameters and its impacts on results allowing statistical assessment of error calculation.

Table 4 – Results on relevant points for DFR calculation obtained from regression line - average value and best case sample in parenthesis

	Simulation	**Measurement (average value)**	**Error** [%]
Tinj @ q_{min} [msec]	1,63	1,53	6,5
Tinj @ q_{max} [msec]	9,70	9,67	0,3
q_{min} [mg/pulse]	3,063	2,491	23,0
q_{max} [mg/pulse]	26,711	26,876	-0,6
DFR	8,7	10,8	-19,4
slope	2,93	3,01	-2,7
Intersection [mg/pulse]	-1,70	-2,21	-23,1

CONCLUSION

Development of 1D simulation model of fuel injector was successfully accomplished. Simulation results show good correlation with real measurements. The highest error accounted was 23% in minimum flow however, under low injection time there are some physical phenomenon that are not fully modeled. Another source of deviation is due to error propagation of linear regression slope and its intersection value in the y-axis. Despite the deviations the model overall accuracy is acceptable to predict in preliminary development stage the fuel injector performance for a given application.

For further development, it is planned to enhance the model in order to minimize errors. The main goal is to improve the flow rate of model in the range of low injector times (less than 2 msec). This could be reached by adding a more realistic modeling of contact force between the needle ball and valve seat (bouncing effect). Moreover, simulation model must considerer stochastic variation using Monte Carlo method to account effect of parameters tolerances on results.

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