DEVELOPING AND VALIDATING A GT-SUITE BASED MODEL FOR A SECOND GENERATION COMMONRAIL SOLENOID INJECTOR

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Abstract: Injection profiles, containing important parameters like injection rate, directly affect the spray structure, fuel-air mixture quality, and as such the physical and chemical processes occurring in the IC engine's combustion chamber. Therefore, injection profiles are one of the keys to improving power, thermal efficiency and minimizing the emission for IC engines. In this paper, a GT-Suite - based simulation model for a second generation solenoid commonrail injector typically utilized in Hyundai 2.5 TCI-A diesel engines, has been successfully developed and validated. The validation is done by using experimental data are acquired by a Zeuch's method-based Injection Analyzer (UniPg STS) in University of Perugia, Italy. The calibration data is measured over a wide range of rail pressure and energizing time (ET) corresponding to the engine operating conditions. The results show that the injector model developed here is reliable and suitable for examining the injector's hydraulic characteristics. The difference in start of injection values obtained through experiment and simulation is only about 15 µs. The total injection volumes obtained through experiment and simulation under ET > 0.8 ms is less than   10 % while the difference is quite high under ET < 0.8 ms and high rail pressure (up to 34.5 %).

Keywords: solenoid injector, Zeuch approach, GT-Suite.

Classification numbers: 5.2.1, 5.10.1.

1. INTRODUCTION

In diesel engines equipped with electronic control unit (ECU), injection rate (IR), injection time (IT), fuel spray development and fuel consumption could be well controlled. Quantifying IR is, therefore, a critically important task in engine research and development. IR could be determined using experiment or simulation. Conducting experiments is obviously expensive as this requires modern equipment with acceptable uncertainties. As such, combining experiment and simulation is normally interested by scientists worldwide. In this approach, simulation models are developed and then validated using experimental outcomes.

Adopting Zeuch methodology [1], Postrioti *et al*. [2] have developed an experimental system named UniPg STS to measure IR and hydraulic characteristics. In the same work, Postrioti *et al*. [2] have also developed a GT-Suite model for a commonrail solenoid injector. The model was validated using the experimental outcomes obtained from the UniPg STS. From the model developed, Postrioti *et al*. [3] have examined IR for a second generation of commonrail injector,

CRI2.5, under split injection strategy with different dwell times (DT).

Bianchi *et al*. [4] have developed a model based on Matlab/Simulink for a first generation Bosch solenoid injector. The model was validated using fuel consumption data experimentally measured by VM-Motori, an engine manufacturer in Italy. An uncertainty of less than 5 % was observed in [4] when fuel consumption was higher than 12 mg; however, the uncertainty is up to 25 % when injecting an average amount of fuel; under a small injection amount (*e.g.* in pilot injection), the uncertainty is up to 40 % [4].

Julien Bohbot *et al*. [5] have developed a 1-D model for a second generation solenoid commonrail injector using AMESim package. The model was validated for two cases: (i) normal single injection for rail pressure = 1600 bar and energizing time ET = 2.2 ms and (ii) multi-injection (pilot and main injection). The results showed that the model could predict the IR quite accurately. An error of less than 5 % is observed over a long ET period, however, under short ET, the error is up to 20 %.

Some other studies have examined the influence of operating conditions on the injection characteristics. Examples include a study conducted by Cavichi *et al*. [6] on the impact of fuel temperature in the injector body on hydraulic characteristics. Using rail pressure signal, Tomi [7] has investigated the injector diagnosis while Qinmiao Kang [8] has developed a technique to isolate the start and end of fuel injection timing.

In our current study a model for a commonrail solenoid injector (CRI2.2) has been developed. This is a typical injection used in diesel Hyundai 2.5 TCI-A engines. The model is designed using GT-Suite package and is validated through the application of the experimental data measured by a UniPg STS system developed in Italy as mentioned earlier. This model is constructed for both single injection and split injection strategies. Details about the single injection and split injection strategies, whose details have been reported earlier in ref. [9]. The experimental data obtained from this work will be used to detail hydraulic characteristics of biodiesel blends under different injection strategies such as single injection and split injection but this will be reported latter in different papers.

2. MODEL DEVELOPMENT FOR A COMMONRAIL SOLENOID INJECTOR USING GT-SUITE PACKAGE

2.1. Studying object and simulation package

CRI2.2, #CRI 0445110275 used in this study is the second generation of solenoid commonrail injector having a maximum injection pressure of 1600 bar [10]. A sectional view of this injector is provided in Figure 1 and its important specifications are shown in Table 1.

Table 1. CRI2.2 injector specifications [10].

TT	Part Name	Commonrail Injector
1	Injector type	Solenoid
2	Number of nozzles	8
3	Nozzle diameter	0.144 mm
4	Maximum number of injections	5 time/cycle
5	Maximum injection pressure	1600 bar
6	Minimum of injection mass	1.0 mm^3/cycle

Currently, there exist a number of simulation packages that could be adopted for injector modeling. For example: Diesel-RK, GT-Suite, Inject32 and AMESim. Among those packages, GT-Suite is developed by Gamma Technologies and includes different powerful tools such as GT-Fuel, GT-Power, GT-Vtrain, GT-Cool, GT-Crank and GT-Vtrain. GT-Fuel allows specialized simulations related to fuel systems including commonrail ones [11]. Especially, GT-Fuel could combine with other packages like GT-Power to simulate engine cycles. With a target to investigate model engine cycles, GT-Suite is adopted in this current study.
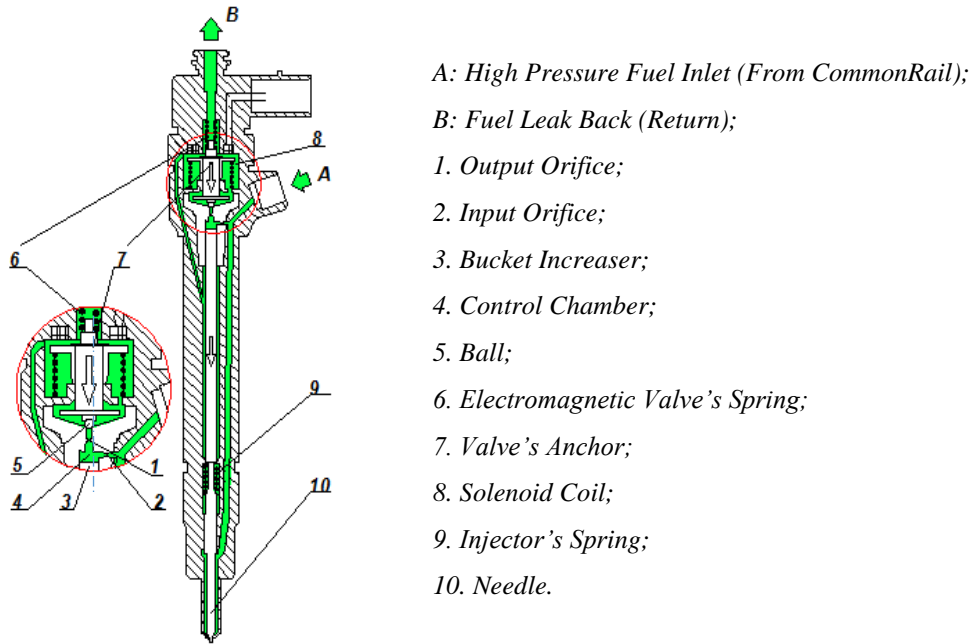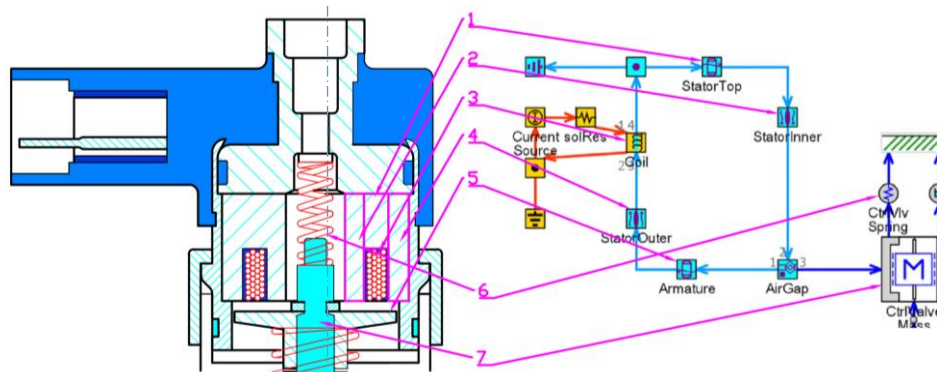

A: High Pressure Fuel Inlet (From CommonRail);

B: Fuel Leak Back (Return);

1. Output Orifice;

2. Input Orifice;

3. Bucket Increaser;

4. Control Chamber;

5. Ball;

6. Electromagnetic Valve's Spring;

7. Valve's Anchor;

8. Solenoid Coil;

9. Injector's Spring;

10. Needle.

Figure 1. Cross section of the CRI2.2 Injector [10].

2.2. Determining input parameters

a) Solenoid valve cross-section   *b) Solenoid valve model*

1- Stator Top; 2- Stator Inner; 3- Coil; 4- Stator Outer; 5- Armature;
6- Electromagnetic Valve's Spring; 7- Valve's Anchor

Figure 2. Electromagnetic Valve of the CRI2.2 Injector.

Element	Parameters	Value	Unit
Stator Inner	Length	12.06	mm
	Cross-section Area	59.32	mm^2
Stator Outer	Length	12.06	mm
	Cross-section Area	147.6	mm^2
Stator Top	Length	6.27	mm
	Inner Diameter	11.32	mm
	Outer Diameter	16.51	mm
Coil	Number Of Turn	36	-
Armature	Length	2.45	mm
	Inner Diameter	8.21	mm
	Outer Diameter	18.04	mm
Air Gap	Gap	0.075	mm
	Cross-section Area	57.42	mm^2

Injector model used for commonrail solenoid injectors like the CRI2.2 investigated in this study is based on three sub-models for electronics, mechanics and fluid dynamics [12]. The model includes main sections as following: solenoid coil, control chamber, bucket increaser, needle, output and input orifices, and hydraulic flows as shown in Figure 1.

Electromagnetic valve

The solenoid model is built from electric and magnetic primitives representing the electromagnetic system: a current source, a coil, stator top, stator inner, stator outer and the air gap between the solenoid and armature (Figure 2b). Dimensions of the solenoid valve were carefully measured in this study using cut-off sections of the injector and this information is provided in Table 2.

Controlling chamber

a) Control Chamber   *b) Control Chamber Model*
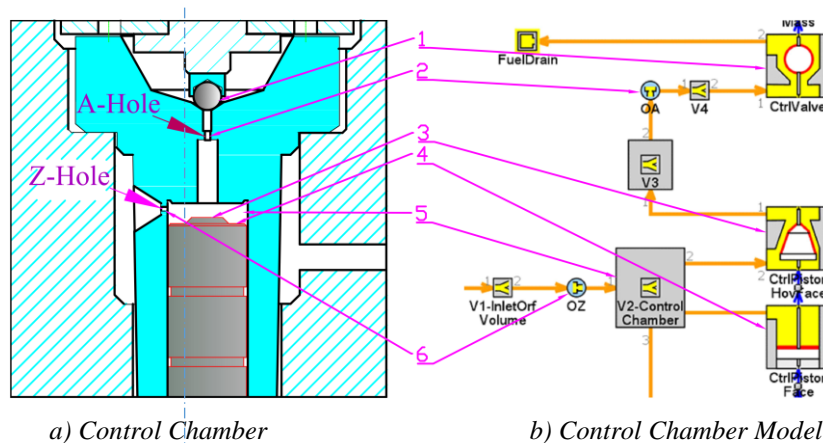
1- Control Valve; 2- Output Orifce; 3- Control Piston HovFace; 4- Control Piston Face;

5- Control Chamber Volume; 6- Input Orifice

Figure 3. Control Chamber Model of CRI2.2 Injector.

Exactly determining the dimensions and weight of chambers and elements located inside the injector is critically important in order to improve the uncertainty of the model developed. Amongst the chambers and elements, dimensions of input orifice A and output orifice Z are ones of the most important parameters having significant influences on the hydraulic characteristics [13] as they cause local cavitations around the chambers especially in the injector nozzle exit. Those parameters were quantified using a high resolution microscopy. Through the measurement, orifice A's diameter, $d_A = 0.2383$ mm and orifice Z's diameter, $d_Z = 0.192$ mm. From those input parameters, a simulation model is shown in Figure 3b.
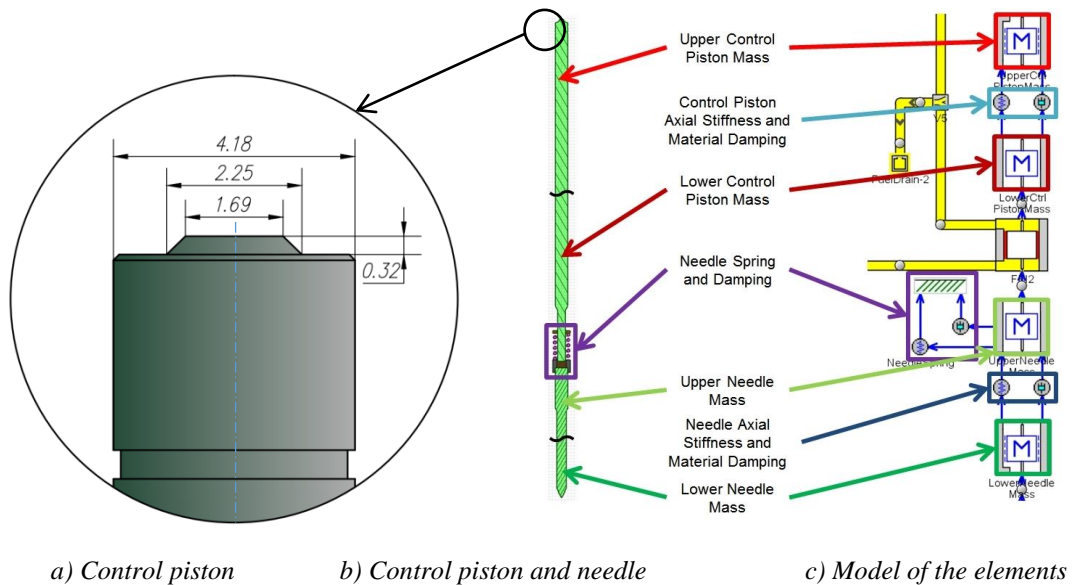
Piston and needle

| a) Control piston | b) Control piston and needle | c) Model of the elements |

Figure 4. Model of control piston and needle mechanics.

| a) Needle tip | b) Needle | c) Model of the elements |

1- Needle piston 1; 2- Needle piston 2; 3- Needle poppet;
4- Nozzle holes; 5- Nozzle line (Annular pipe); 6- Engine cylinder
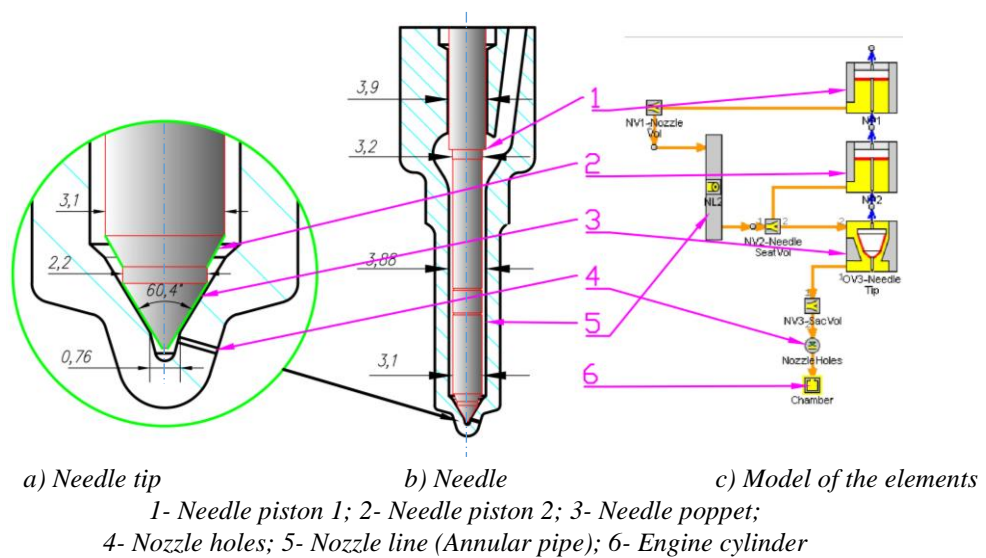
Figure 5. Model of needle pressure forces.

The stroke of needle depends on the combination of forces acting on the top and bottom of the piston, the needle and its spring. Those forces are quantified through the fuel pressure exerted on the effective surface of piston and needle. Due to high fuel pressure, piston and needle could be axially compressed and distorted, as such the model for piston and needle is separated into two equal sections being connected through a spring and a damper as shown in Figure 4 [14]. Geometric dimensions and mass of piston and needle measured in this study are provided in Figures 4 and 5.

2.3. Some output parameters from the injector model

The built-in injector model developed in GT-Suite allows to determine the IR pattern, the amount of fuel injection according to the inputs ET and rail pressure in both single injection and multi-injection cases. The model can also work with the different fuel types including biodiesels. Some output parameters of injector model in single injection case are shown in Figure 6.
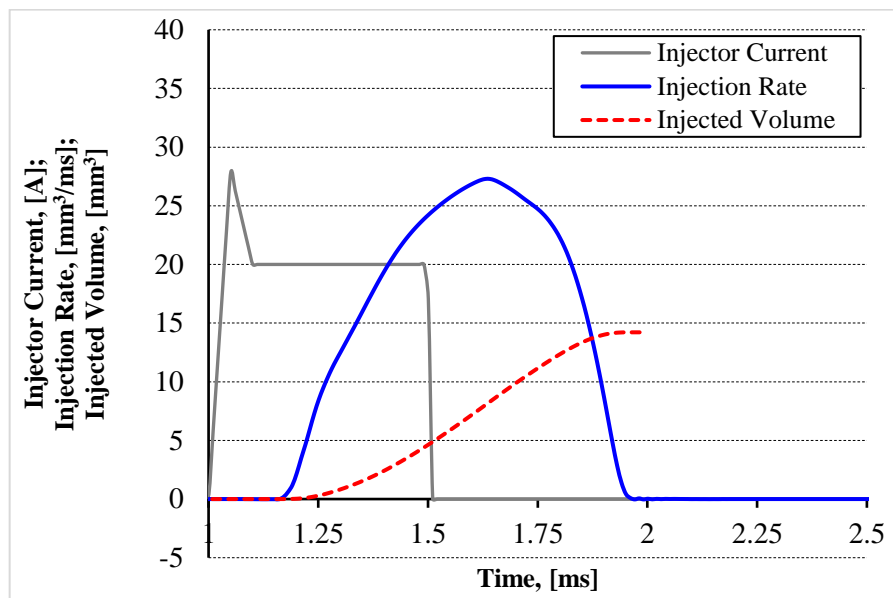

Figure 6. The output parameters of injector model in case of a Single Injection event.

3. MODEL VALIDATION

3.1. Experimental system and measuring modes

Experimental system

The model developed in this study for the CRI2.2 injector is validated using input parameters (rail pressure, energizing time) and output parameters (injection time, injection duration, injection amount, and injection rate). As mentioned above, those parameters have been measured using the UniPG Injection Analyzer Shot-to-shot developed at the SprayLab University of Perugia, Italy. This experimental system allows to simultaneously and accurately determine the energizing pulse, injection rate, and rail pressure development [1, 2, 6, 15] and thus is suitable for testing different

fuels (*e.g.* gasoline, diesel, and biodiesels) and for different injection strategies (like multi-injections including split injections).
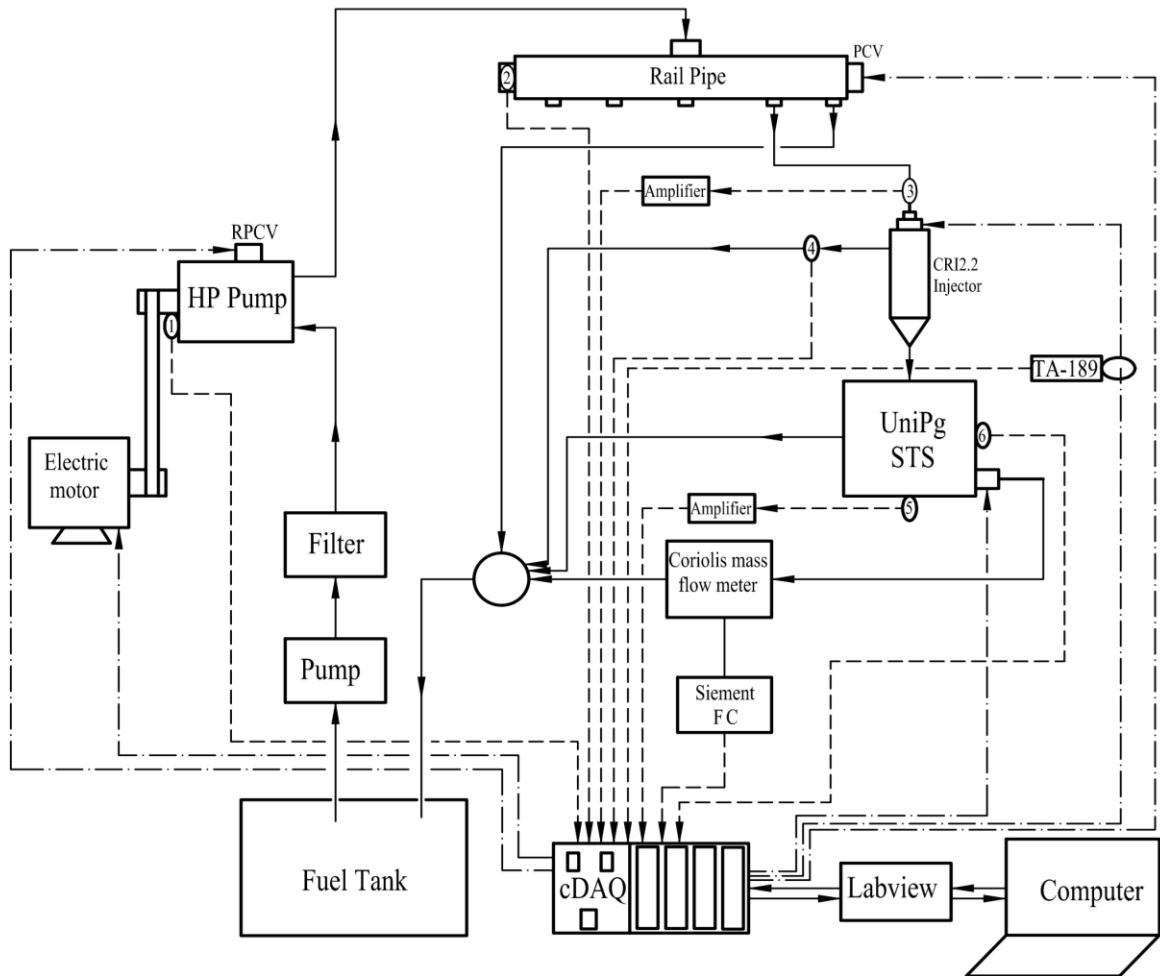
UniPg STS- UniPg Injector Analyzer; 1- encoder; 2- rail pressure sensor; 3- pressure sensor; 4- return fuel pressure and temperature sensor; 5- pressure sensor; 6- temperature sensor; TA-189- current clamp;

Figure 7. Illustration of experimental setup [1].

The experimental test bench, developed at the SprayLab, University of Perugia, is schematically shown in Figure 7 [1]. The CRI2.2 injector is placed into the measuring chamber of the UniPg STS injector analyzer. The pressure signal in the measuring chamber, along with the fluid temperature, is detected by a piezo-resistive sensor (Kistler 4075 A100). An Amplifier (Kistler 4618A2) is used to amplify the pressure signal before supplying to cDAQ (Ni-cRIO 9074). Fuel passes through the measuring chamber by a solenoid valve. The fluid escaping from the Injection Analyzer flows through a Coriolis mass flow meter (Siemens Sitrans CF 2100) to measure the mean mass flow rate of fuel injected and the fuel density over an assigned set of injector actuation cycles. The injection pressure in the system is controlled based on the pressure sensor signal in the rail pipe (3), the opening of the pressure regulating valve on the rail pipe (PCV), and the flow control valve (RPCV) on the high pressure pump. The electrical pulse signal used to control the injector is directed by the current clamp (TA-189) connected to cDAQ. All

control signals for injection systems and injectors as well as measured signals are processed by an inhouse Labview code. More details about the UniPg STS Injection Analyzer and the code are reported in [1, 16].

Experimental modes

The model developed here is validated using two experimental modes, namely single injection and split injection. Single injection mode was conducted at rail pressures = 600 bar, 1000 bar, 1400 bar and 1600 bar; ET varies from 0.3 ms to 1.2 ms (equivalent to the actual operation range observed in this study in a Hyundai 2.5 TCI-A engine). Split injection strategy investigated in this study is limited to double injection modes and the strategy was conducted at rail pressure = 1000 bar, injection ratios between two injections in the double injection modes are (i) 30/70 (corresponding to energizing times of those two injections ET_1 = 0.55 ms and ET_2 = 0.82 ms, respectively) and (ii) 50/50 (corresponding to energizing times of those two injections ET_1 = 0.59 ms and ET_2 = 0.59 ms, respectively).

3.2. Results and discussion

With similar input parameters (energizing pulses and rail pressure), errors/uncertainties of the model developed in this study are evaluated through comparing experiment and simulation results obtained under different injection rate conditions. Figure 8 compares injection rates obtained through experiment and simulation at a rail pressure of 1000 bar (Figure 8a) and 1400 bar (Figure 8b), respectively.

It is clearly shown from Figure 8 that injection rates, start and end of injection events, maximum injection rates obtained through GT-Suite are quite well matched with the experimental results. However, it is worth noting that uncertainties are high under short ET. Under ET > 0.8 ms, the difference in start/end of injection times obtained through experiment and simulation is only about 15 µs. Under ET < 0.8 ms, the difference is up to 150 µs as shown in Figure 8.

It is also shown in Figure 8 that some significant differences are observed in some certain times during the injection period and this is probably due to the uncertainties in measuring dimensions of chambers and elements. Some characteristics of the chamber and elements are very hard to quantify (*e.g.* surface roughness of the chambers, variations of initial forces of needle spring as well as solenoid valve's spring; or the changes in the resistor of solenoid valve due to fuel temperature which was not accounted in this model). High uncertainty obtained under short ET compared to that under longer ET can be attributed to the disregard of variations of nozzle discharge coefficient as well as cavitation coefficients of orifices A and Z.

Table 3 compares the total injection volumes obtained through experiment and simulation. It is shown that the differences between the total injection volumes obtained through experiment and simulation under ET > 0.8 ms is less than 10 %. The differences between the total injection volumes are quite high under short ET and a high rail pressure. Table 3 also shown, under ET = 0.3 ms and rail pressure = 1600 bar, the difference is 34.5 %. The high differences observed under short ET are in a good agreement with the outcomes observed at injection rates as discussed earlier in this section.
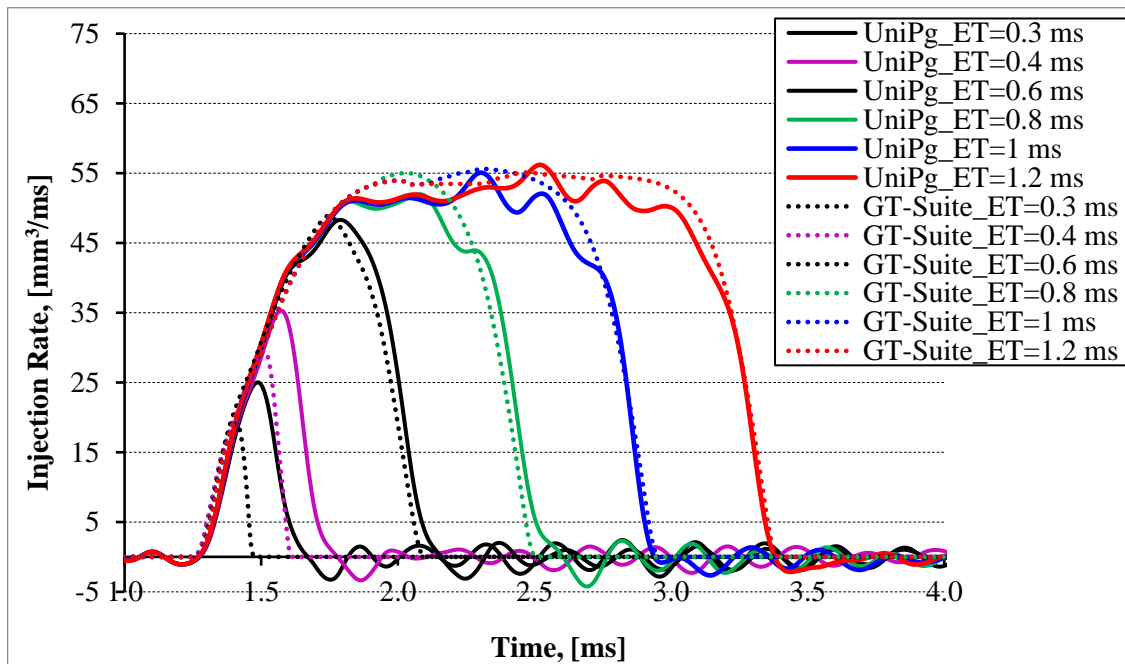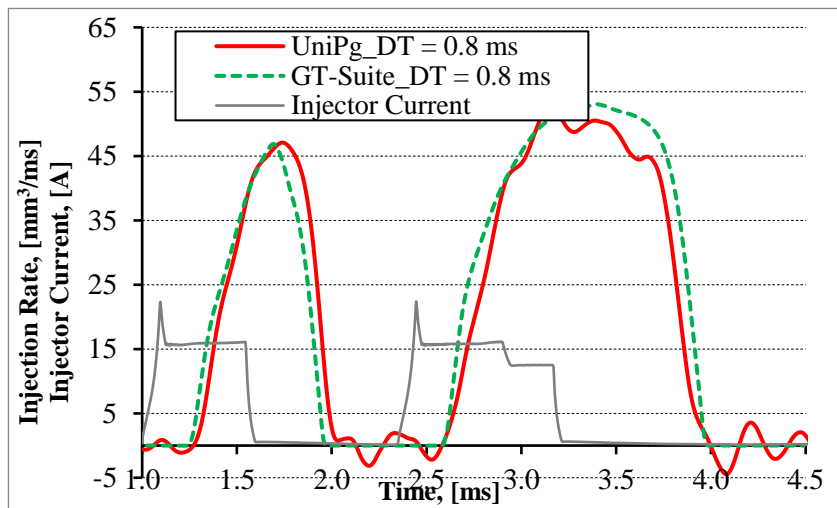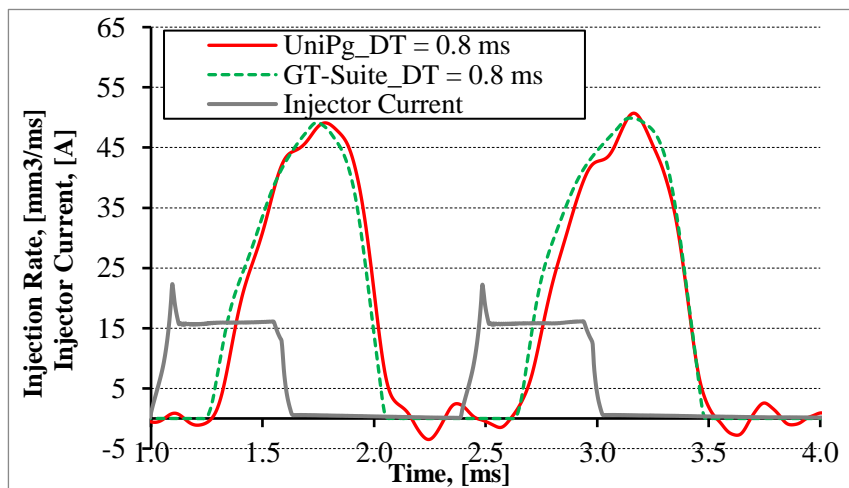
a) 1000 bar
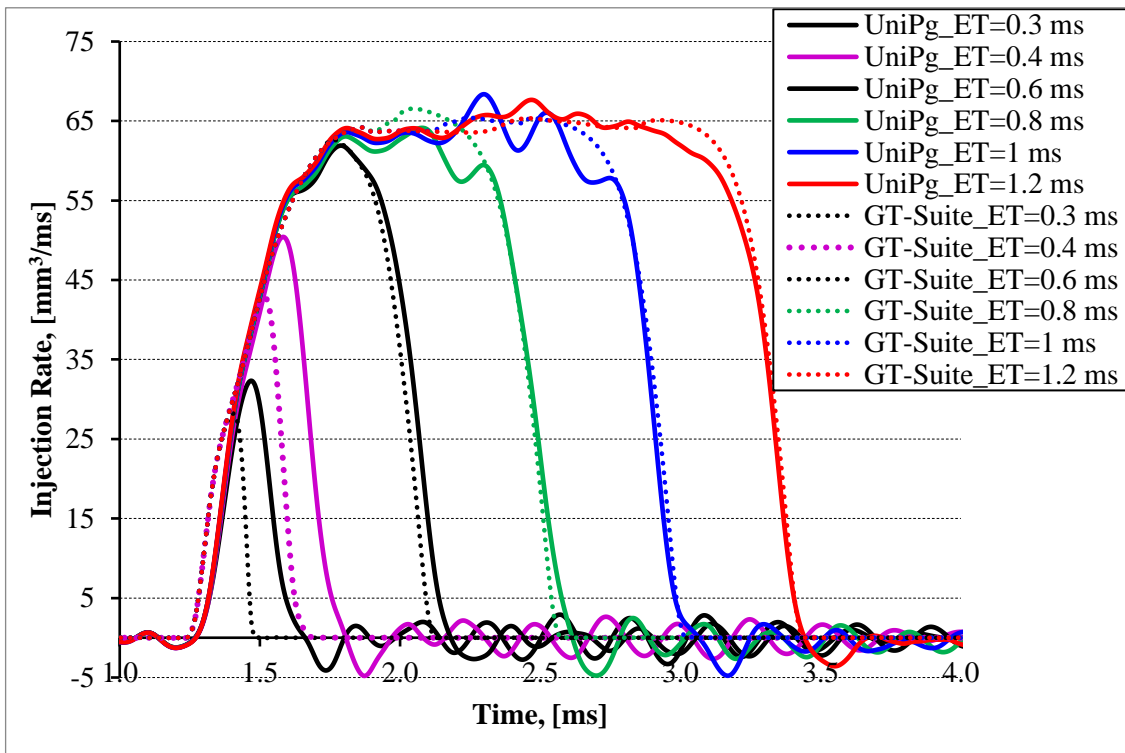
b) 1400 bar

Figure 8. Comparison of the experimental volume flow rate with the simulation results at a rail pressure of 1000 bar and 1400 bar in case of single injection events.

Table 3. Comparison of the experimental injected volume with the simulation results at a rail pressure of 600, 1000, 1400 bar and 1600 bar in case of single injection events.

ET, [ms]	rail pressure = 600 bar			rail pressure = 1000 bar			rail pressure = 1400 bar			rail pressure = 1600 bar		
	Injected Vol., [mm³]		Error	Injected Vol., [mm³]		Error	Injected Volume, [mm³]		Error	Injected Volume, [mm³]		Error
	GT Suite	UniPg STS		GT Suite	UniPg STS		GT Suite	UniPg STS		GT Suite	UniPg STS	
0.3	2.57	2.58	*0.3%*	3.14	4.8	*34.4%*	4.76	5.82	*18.2%*	4.56	6.96	*34.5%*
0.4	4.45	4.94	*10%*	7.51	8.68	*13.5%*	10.66	13.72	*22.3%*	12.7	16.24	*21.8%*
0.6	12.92	14.32	*9.8%*	24.67	25.49	*3.2%*	35.56	36.31	*2.1%*	40.75	41.07	*0.8%*
0.8	24.59	26.77	*8.1%*	46.55	46.48	*-0.2%*	64.52	62.53	*-3.2%*	71.59	70.44	*-1.6%*
1.0	45.51	41.43	*-9.9%*	70.59	67.86	*-4.0%*	92.96	90.43	*-2.8%*	101.71	101.96	*0.2%*
1.2	59.12	56.93	*-3.8%*	94.04	91.03	*-3.3%*	119.93	118.31	*-1.4%*	122.63	124.86	*1.8%*

a) 30/70

b) 50/50

Figure 9. Comparison of the experimental volume flow rate with the simulation results at a rail pressure of 1000 bar in case of Split Injection events at ratios of 30/70 and 50/50.

Figure 9 compares injection rates obtained through experiment and simulation under split-injection modes (double-injection modes examined in this study) at a rail pressure of 1000 bar. As mentioned earlier, two injection ratios investigated here, namely 30/70 and 50/50, are shown in Figure 9a and 9b, respectively.

Similar to results obtained under single injection modes, simulation injection rates, start and end of injection times under split injection modes are quite close to those obtained through experiment. The results obtained from this simulation show that the model developed here has high accuracy and necessary reliability to examine complex injection strategies like the split injection investigated here. The model is a useful tool for the authors to continue studying the hydraulic characteristics when utilizing multi-injections including split-injections and for different fuels including biodiesels and their blends with the fossil diesel.

4. CONCLUSIONS

Using GT-Suite package, this study has successfully developed a model for a commonrail solenoid injector. The model developed here includes 3 sub-models including mechanical model, hydraulic model and electronic model. The model was carefully validated using experimental data obtained from the UniPg STS developed by the SprayLab, University of Perugia, Italy. In order to assure high accuracy for the model, three important issues have been investigated in this study: (i) accurately quantifying dimensions of chambers and elements inside the injector, especially diameters of orifices A and Z and dimensions of the control chamber; (ii) experimentally measuring important injection parameters under a wide range of operating conditions (*e.g.* rail pressure from 600 bar to 1600 bar; ET from 0.3 ms to 1.2 ms corresponding to the operating ranges observed in this study in a Hyundai 2.5 TCI-A engine); and (iii) developing and validating the model for both single injection and split injection strategies.

CRediT authorship contribution statement. Dat X. Nguyen: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation. Vu H. Nguyen: Visualization, Investigation, Supervision. Phuong X. Pham: Validation, Writing- Reviewing and Editing.

Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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