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

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Received: 28 December 2020; Accepted for publication: 21 March 2021

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,
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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.

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

2.2. Determining input parameters

Figure 2. Electromagnetic Valve of the CRI2.2 Injector.
Table 2. Geometrical and electrical parameters for electromagnetic valve.

| 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**

![Controlling chamber](image)

*a) Control Chamber*  
*b) Control Chamber Model*

1- Control Valve; 2- Output Orifice; 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, $d_A = 0.2383 \text{ mm}$ and orifice Z’s diameter, $d_Z = 0.192 \text{ mm}$. From those input parameters, a simulation model is shown in Figure 3b.

**Piston and needle**

![Diagram of piston and needle](image)

Figure 4. Model of control piston and needle mechanics.

![Diagram of needle](image)

Figure 5. Model of needle pressure forces.
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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.](image)

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).

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
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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 ET₁ = 0.55 ms and ET₂ = 0.82 ms, respectively) and (ii) 50/50 (corresponding to energizing times of those two injections ET₁ = 0.59 ms and ET₂ = 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.
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]     | Injected Vol., [mm³]     | Injected Volume, [mm³]   | Injected Volume, [mm³]   |
|          | Error                    | Error                    | Error                    | 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%                      |

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 common-rail 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.

Acknowledgement. We would like to express our special thanks of gratitude to Professor Lucio Postrioti and Dr. Andrea Cavichi at Spray Laboratory – Perugia University – Italy who have offered the great opportunity for us to use the exceptional experiment facility at Perugia. It would not have been possible to have this work done without your useful support prior and during the experiment.

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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