Method for determining the parameters of injection of Common Rail injectors

Sergey G Belchev
Department of Automotive Engineering and Technologies, Faculty of Mechanical Engineering and Technologies, Technical University - Varna, 1 Studentska Str., city of Varna, Bulgaria
sergtu@abv.bg

Abstract. The flow rate through the holes of the nozzle at constant pressure and steady flow is an important feature of electronically controlled injectors. The flow rates at different pressure of injection determine the main characteristic of Common Rail injectors. In scientific researches it is necessary to determine this flow rate experimentally. This requires specially equipped experimental installations and expensive measuring devices. The article presents a method for determining the steady flow rate through the holes of the nozzles using a standard test bench for Common Rail injectors. The method is based on the assumption that, all else being equal, non-steady phenomena at the beginning and end of the injection and displacement of injection to the control pulse are identical at different injection timing. Under this conditions we can easily determine the steady flow rate through the holes of the nozzle.

1. Introduction
In modern diesel engines with Common Rail fuel system the injected fuel quantity is controlled by injectors. Injected fuel quantity is implemented, setting the injection timing at a given injection pressure. The injectors are electronically controlled and the time during which they are open and inject fuel is determined by the duration of control electronic pulse.

The magnitude of fuel flow rate through the holes of the nozzles at different injection pressures is an important feature of these injectors. There are three different stages of injection with longer duration. The first opening stage of injector is characterized by non-steady flow with increasing flow rate. The third closing stage of injector is characterised by non-steady flow with decreasing flow rate. During the second stage, when the nozzle needle is fixed and fully open, flow of leakage with constant flow rate is established. Precisely this constant flow rate determines the injector feature and is needed to design and test Common Rail injectors. It is determined theoretically in design calculations and experimentally in the presence of a real injector. Experimental calculation, however, faces many difficulties. Expensive devices and complex experimental installations are needed to determine the steady flow rate through the holes of the nozzles.

The objective of this work is to determine this important feature of Common Rail injectors, using standard test benches for such injectors. In addition, the test results need to be processed, using simple mathematical device in order to avoid any additional inaccuracies in the obtained flow rates through the injectors.
2. Prerequisites and Basic Concepts

Injected fuel quantity of Common Rail electromagnetic injectors is controlled with the help of electronic pulse of a certain nature and duration. The electronic pulse nature is known [1]. It is determined by the intensity of the current passing through the solenoid valve and consists of several phases (a, b, c, d, e), figure 1. The pulse nature is determined by the need for opening the valve quickly and for closing it immediately after interruption of the pulse. The letter "F" on the figure shows the injection end, the letter "t" shows the control pulse duration and a "t_{inj}" shows the injection timing.

![Diagram of injection process](image)

**Figure 1.** Stages of a traditional injection process.

In fact, the movement of solenoid valve armature and related ball is delayed compared to that of the electronic pulse [1]. The valve opens later and closes later. The pressure cycle in valve control chamber also lags behind the valve movement, the nature of this cycle not copying the valve movement but determined by it [2]. The pressure cycle in valve control chamber is a direct reason to drive the valve control plunger connected with the nozzle needle. In general, the needle movement due to the changing pressure in valve control chamber lags behind that of the control pulse, figure 1. When moving, the nozzle needle opens the nozzle openings and determines the beginning, duration, and end of the fuel injection process [2], [3].
At the beginning of needle lifting, while the clear opening in the nozzle needle seat taper is less than its openings, the fuel flow rate increases sharply and reaches certain constant value at a given needle position. The next needle movement up to its final position does not change the magnitude of fuel flow rate. A period of detected leakage at constant flow rate follows. During the needle closing, fuel flow rate remains constant for some time, and then it sharply reduces until the final stop of the needle movement, figure 1. Except for the start and end phases with variable flow rate, the average constant value of the fuel flow rate during the injection should be determined.

In case of longer injection and control pulse duration, and nature of change in fuel flow rate it may be concluded that the nature of change in fuel flow rate does not depend on the pulse duration. The nature of fuel flow rate initial increase and late injection do not depend on the control pulse duration. There are many factors that influence the nature of initial injection, but if they are the same for the same injector and will therefore not change the beginning of injection. The same applies to the end of injection. In case of sufficient injection timing, the phenomena accompanying needle opening subside and a steady flow with constant flow rate is established. It is therefore assumed that the phenomena accompanying the nozzle needle closing and nozzle late closure do not depend on the length of the previous period of detected leakage as long as this duration is sufficiently large.

![Diagram showing fuel flow rate and solenoid current](image)

**Figure 2.** Method for determining the steady flow rate $G_{spr}$.

The considerations outlined above lead to the conclusion that the increased sufficiently long duration of control pulse results in increase in the injection timing with the same value, which the control pulse is increased with. The increased injected fuel is at the expense of the increased time of detected leakage at constant flow rate. This is illustrated in figure 2. On the figure, $Q_b$ indicates the quantity of fuel injected during the initial lifting of nozzle needle. $Q_e$ is the quantity of fuel injected after the control pulse is interrupted, which includes non-steady mode in the needle closing. $Q_1$ and $Q_2$...
indicate the total quantity of fuel injected at control pulse duration of \( t_1 \) and \( t_2 \), respectively. These fuel amounts are proportional to the area under the fuel flow change curves. The injection timing at a different control pulse is indicated by \( t_{inj1} \) and \( t_{inj2} \), respectively.

Therefore, it could be argued that:

\[
q_{inj1} - q_{inj2} = t_1 - t_2
\]  

(1)

As outlined in the considerations above and as shown in figure 2, the simple dependence for calculating \( G_{Vst} \) - fuel flow rate value - may be determined at a steady flow of leakage:

\[
G_{Vst} = \frac{q_1 - q_2}{t_1 - t_2}, \text{ cm}^3/\text{s}
\]  

(2)

With the help of formula (2), it is possible to calculate the value of the constant flow rate through the holes of the nozzles for a real injector. It is only needed to experimentally determine the injected fuel for this injector at two different durations of the control pulse, all else being equal. Injectors can be tested on a standard test bench for Common Rail injectors which provides sufficient accuracy of the measured fuel quantities. The expansion of experiment will allow calculation of the flow rate at different pressures and determination of the real injector feature.

3. Experimental Studies

The experiments demonstrating the above statements are made on a standard test bench for Common Rail injectors CRI-NTR816E. The elements of the system for pressure generation, measurement and control are produces by the company BOSCH. The measurement is made by Cobolt system, with accuracy of the measurement of 0.1 mm\(^3\). The studies were conducted with a BOSCH working injector having number 0445110044.

The injected fuel quantities are measured at three different pressure levels in the fuel rail - 135MPa, 80MPa and 25MPa. Four different control pulse durations - 1800\( \mu \text{s} \), 1500\( \mu \text{s} \), 1200\( \mu \text{s} \) and 900\( \mu \text{s} \) - are obtained for each pressure level. Three measurements are made for each experiment points and the results are averaged.

\[
Q_m = \frac{q_1 + q_2 + q_3}{3}, \text{ mm}^3
\]  

(3)

\[
G_{Vst} = \frac{1000Q_m}{t}, \text{ cm}^3/\text{s}
\]  

(4)

Table 1 shows the experiment results. The last column shows the flow rate value calculated with the help of formula (4). It is not real, since the injection time is not equal to the control pulse duration but can be used for comparison.

Formula (2) calculates \( G_{Vst} \) - flow rate values - at detected leakage using various pulse duration combinations. The results obtained for the three pressure levels in the fuel rail are presented in table 2. The first row of the table shows the time values in (\( \mu \text{s} \)) which are used to make the calculations.

4. Analysis of the Experimental Results

As apparent from table 2, the various combinations of pulse durations lead to different \( G_{Vst} \) flow rate values. The average values are closest to the results obtained at selected values \( t_1=1800\mu\text{s} \) and \( t_2=900\mu\text{s} \), (1800-900). This is the logical consequence of the fact that the difference between the two times is the highest which minimises the error of temporary disturbances during injection at a steady flow. If the difference in the duration of pulses used is smaller, small deviation from the steady flow permanent nature resulting from wave phenomena may be expected.
Table 1. Experiment results

| Pinj (MPa) | 1800 | 1500 | 1200 | 900  |
|------------|------|------|------|------|
| 135MPa     |      |      |      |      |
|            | 86.5 | 75.9 | 60.6 | 48.0 |
|            | 86.9 | 76.1 | 61.2 | 48.3 |
|            | 86.6 | 76.4 | 62.7 | 48.4 |
|            | 86.67| 76.13| 61.50| 48.23|
|            | 48.15| 50.75| 51.25| 53.59|
| 80MPa      |      |      |      |      |
|            | 65.4 | 55.1 | 44.9 | 34.7 |
|            | 65   | 55.8 | 45.3 | 35.2 |
|            | 65.13| 55.57| 45.4 | 35.3 |
|            | 36.18| 37.05| 37.67| 38.97|
| 25MPa      |      |      |      |      |
|            | 32.4 | 26.9 | 18.3 | 11.6 |
|            | 32.7 | 26.9 | 18.5 | 11.8 |
|            | 32.8 | 27.8 | 19.4 | 11.8 |
|            | 32.63| 27.20| 18.73| 11.73|
|            | 18.13| 18.13| 15.61| 13.03|

Table 2. Calculated $G_{vst}$ flow rate values at steady leakage flow

| Pinj (MPa) | 1800-1500 | 1800-1200 | 1800-900 | 1500-1200 | 1500-900 | 1200-900 |
|------------|-----------|-----------|----------|-----------|----------|----------|
| 135MPa     | 35.11     | 41.94     | 42.70    | 48.78     | 46.50    | 44.22    |
| 80MPa      | 31.89     | 33.22     | 33.41    | 34.56     | 34.17    | 33.78    |
| 25MPa      | 18.11     | 23.17     | 23.22    | 28.22     | 25.78    | 23.33    |

To obtain adequate results with a small error, the duration $t_i$ should not be less than 900μs. When testing a specific injector, an experiment can be made by increasing the injection times and the interval between them to detect the smallest values after which the increase does not result in a significant change in the calculated values of the established $G_{vst}$ flow rate.

When comparing the relative indicator $Gv'$ with the calculated $G_{vst}$ values, it can be concluded that at higher injection pressures (135MPa, 80MPa) $Gv'$ is higher than $G_{vst}$. At a low pressure of 25MPa, $Gv'$ is lower than $G_{vst}$. The likely explanation of this fact is:

- At high injection pressure, the needle response time during its opening is less, due to the higher absolute pressure drop in the valve control chamber and vice versa - the needle closing takes more time due to the slower pressure equalization in the valve control chamber. This increases the injection time and it may exceed the control pulse time;

- At low injection pressure, the needle response time is increased and the delay of initial injection is also increased compared to that of the initial pulse. On the other hand, the needle closes faster due to the faster pressure equalization in the valve control chamber. This reduces the injection time to the control pulse duration.

Figure 3 illustrates the change in the nature of injection at equal times of the control pulse and different injection pressures.

Figure 3 shows the injection parameters at low pressure (lp) and at high pressure (hp). It also shows approximately the average injection flow rate calculated by formula (5), where the fuel injected is relative to the injection time.
This average flow rate value cannot be calculated using the presented methodology, since the injection time is unknown. However, based on the methodology, information on the relative injection time compared to the pulse duration can be obtained:

- if \( Gv' \) is higher than \( G_{V_{th}} \), then \( t_{inj} \) is higher than \( t \) - at a relatively high injection pressure;
- if \( Gv' \) is lower than \( G_{V_{th}} \), then \( t_{inj} \) is lower than \( t \) - at a relatively low injection pressure.

There is obviously a pressure where \( Gv' \) is equal to \( G_{V_{th}} \) and therefore \( t_{inj} \) is equal to \( t \). It is possible to find out this pressure at which the above values are equal with a series of experiments.

5. Conclusion
In the presence of a test bench for Common Rail injectors, and with the help of the presented methodology, it is possible to easily and accurately determine the flow rate through the holes of the nozzle at detected leakage flow.

The pulse duration should be relatively large, more than 900\( \mu \)s, to ensure a period of detected leakage.

In case of greater difference in the duration of pulses used in the calculation, more precise results are obtained.

The deviations of the obtained debit rates are greater at very high pressure levels. In such cases pulses with greater difference between them are needed.

Based on the methodology, additional conclusions on the nature and duration of fuel injection can be made.

6. References
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