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# Fuel injection and combustion study by the combination of mass flow rate and heat release rate with single and multiple injection strategies

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ABSTRACT

The injection and combustion characteristics are complicated when split injection strategy is used due to strong interaction between splits. Various injection tests were carried out with long tube real-time fuel flow measuring instrument by employing both single and split injection strategies. Many engine tests with selected operation points (various pilot injection quantities, various injection dwells and various numbers of split injections) were also carried out with split injection strategy, enabling the combination of mass flow rate (MFR) and heat release rate (HRR) information to study combustion features. The results showed that raised injection pressure shortened the injection delay and increased the MFR. The actual injection duration was much longer than the TTL duration. More importantly, for multiple injections, the interaction between splits was dominated by the duration of the first split and injection intervals. The number of splits also exerted profound influence on the interaction. In addition, higher MFR for pilot injection near the piston TDC adversely affected the HRR and normalized combustion efficiency. Increased split injections with low MFR can effectively lower the peak HRR thus reducing the maximum temperature and $NO_x$ emissions.



## 1. Introduction

The MFR and injection features are of great importance for the combustion characteristics and emissions as the spray characteristics largely depend on the fuel mass rate [1,2]. The injection features for a host of fuels and the effects of MFR on engine performance with single injection strategy were extensively investigated by many researchers [3–6]. Desantes [7] experimentally studied the combustion and emission characteristics to find the impacts of the shape of MFR. The results suggested that "boot-like" fuel MFR shape could improve the trade-off between engine performance and emission, decreasing the $NO_x$ with a slight penalty of soot and BSFC. According to Ramírez [8], lower initial MFR led to lower HRR, prolonged ignition delay and lower maximum HRR, leading to the reduction of $NO_x$. Higher initial MFR contributed to earlier appearance of peak temperature. Higher MFR is favorable for main injection as it boosts the mixture formation and soot consumption. In Keiki's study [9], the initial injection was controlled through a low pressure CR while the main injection was governed by switching to a high CR, allowing high flexibility to control the MFR. It was found that PM reduced by 40% while $NO_x$ emission kept constant. The premixed combustion can be regulated through the control of MFR, and higher MFR caused higher diffusion combustion HRR and cylinder pressure. Kato [10] reported that quicker injector opening allowed longer distance penetration to develop and better mixture to form. Consequently, the soot level halved while the $NO_x$ level showed little change.

Multiple injections (close-coupled) which show complex injection characteristics can effectively improve engine performance compared with single injection strategy [11,12]. Mohammad and Álvaro [13,14] studied the influences of fuel quantity distribution between split injections and dwell on engine performance and reported that exhaust emissions can be potentially reduced without economy penalty. Carlucci [15] pointed out that split injection can effectively boost the cold start and cold idle performances because of better fuel mass distribution and fuel mixture. To investigate the behavior of splits, Kourosh [16] employed Mie scattering technique and PLIF to study the spray macroscopic characteristics. It was reported that the second split injection shows higher velocity. The results also showed that split injections present less injected fuel mass than the single injection case.

Although many successes have been made, the split injection strategy has not been sufficiently studied. How the split injection strategy impacts the engine performance is still not well known as the injection and spray show strong dependence on injector technology (injector structure, driven model and needle motion) and injection condition (injection pressure, fuel flow regime and fuel temperature). The injection characteristics with split injections are significantly different from single injection because the needle reciprocates several times in a short time, causing complicated needle motion and injection characteristics [17]. The splits interact with each other to different degrees with a wide range of injection dwells and injection durations, and the MFR interaction is thought to

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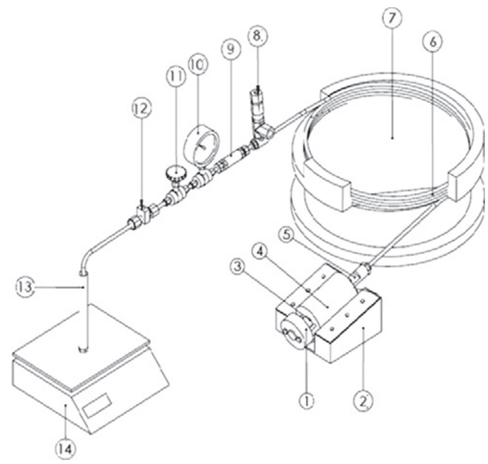


1-Lock; 2-Injector holder base; 3-Injector; 4-Injector holder; 5-Strain gauges; 6-Measuring tube; 7-Tube holder;
8-Relief valve; 9-Filter; 10-Pressure gauge; 11-Needle valve; 12-Thermocouple holder; 13-Cylinder; 14-Weighing scale;

**Fig. 1.** Isometric view of the MFR measurement instrument (adapted from [19]).

significantly affect the injection characteristics. In addition, the interaction between different injections in terms of spray propagation, fuel dispersion and entrainment of burnt gases from the combustion of the preceding injection(s) in a given thermodynamic state in the combustion chamber has not been sufficiently investigated.

This paper aims to study the injection characteristics of split injection strategy and their effects on the engine performance from the perspective of the combination of fuel MFR and HRR. First, to present a deep insight into the injection features, both single and split injection strategies were applied to carry out numerous injection tests. The long tube measuring instrument was applied to measure the MFR. Many engine tests with selected operation points were then carried out with split injection strategy, enabling the combination of MFR and HRR to reveal some basic combustion regimes.

## 2. Experiment apparatus

The MFR measurement was performed with a long tube measuring system built in-house according to the principle of Bosch method [18] with an improved method of measuring the pressure pulses using external strain-gauges. The schematic of the improved instrument is shown in Fig. 1. Through the lock (1), the injector (3) is fixed to the injector holder (4) which connects to measuring tube (6). Two strain-gauges (5) positioned at the very outlet of the injector are used to detect the pressure signals. A relief valve (8) is employed to avoid damaging the instrument if over pressurized. The needle valve (11) is used to regulate the back pressure (Pb) in the measuring pipe (6) and Pb can be read through the pressure gauge (10). A thermocouple can be installed on the thermocouple holder (12) to monitor the fuel temperature. The volume of the injected fuel can be measured through the cylinder (13) while the weight can be measured through the weighing scale (14). To avoid trapping air in the measuring tube, a lean injector holder base (3) and tube holder (7) are employed to make coils of the measuring tube go up gradually.

**Table 1**
Engine specifications.

| Bore | Stroke | Displacement volume | Compression ratio | Connecting rod length |
|---|---|---|---|---|
| 84.0 mm | 90.0 mm | 2993 $cm^3$ | 16.1:1 | 160.0 mm |

High measuring accuracy (over 94%) and repeatability can be obtained with this instrument after careful calibration. For each test, 5 groups of injection (200 injections for each group, meaning 1000 injections in total for each test) were carried out. For each group, the accumulated fuel mass obtained by integrating the MFR was used to compare with the actual injected fuel mass (obtained by measuring with a weighing scale). The results showed high accuracy with the error of less than 6%. Comparison of fuel mass gained from integration among the 5 groups presented the highest variation of 5.8%. The result for each test was finally obtained by averaging the total result of the 1000 injections.

A piezo driven convergent injector which was the same as the one fitted to the engine was employed. It is an 8-hole round inlet injector with outlet hole diameter of 0.118 mm. The conicity $AF = (d_i^2 - d_o^2)/d_i^2$ is 19%. A 3.0 l V6 Lion Diesel Engine was used to perform the combustion tests by employing split injection strategy. The engine is equipped with twin-turbocharger and a common rail injection system. The specifications are shown in Table 1 and more details can be found in [20].

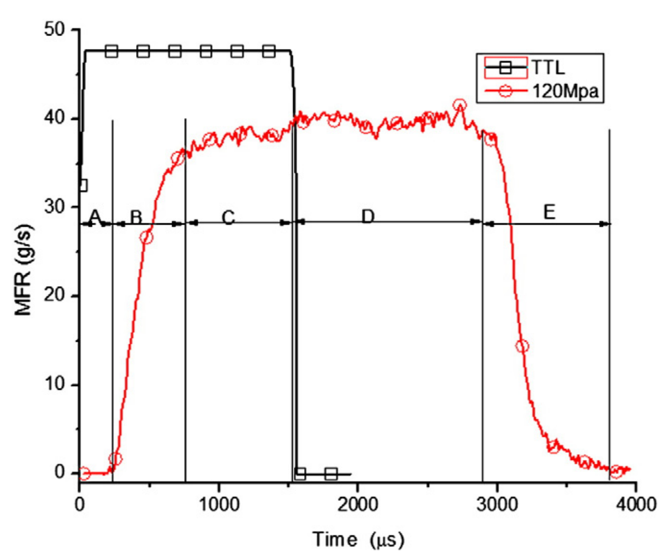


**Fig. 2.** Shape of the MFR signal under 120 MPa.