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# Measurement and validation of hole-to-hole fuel injection rate from a diesel injector

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ABSTRACT

Hole-to-hole fuel injection characteristic differences that occurs during injection, results in non-uniform fuel distribution and compromised combustion and emission in direct injection IC engines. Hence the instantaneous determination of these differences could help in understanding and the improvement of combustion characteristics. In this paper, a hole-to-hole transient measuring method based on the spray momentum flux theorem was developed and used to determine the fuel injection rate from each nozzle hole of a multi-hole diesel injector. The customized measuring method, was further used to study the characteristics of injection from multi-hole nozzle. Injection rates from the multi-hole nozzle, were compared with those measured with an EFS IFR-600 which is widely used to measure the total injection rate of diesel injector. And about 1% discrepancy in terms of cycle fuel injection quantity, was obtained. Additionally, the fuel injection rate from each nozzle hole of a double layered eight-hole diesel injection nozzle were measured and analyzed. It was found that the cycle fuel injection quantities of the lower layered nozzle holes (4 holes) were 5–15% greater than the cycle fuel injection quantities of the upper layered nozzle holes (4 holes). This was attributed to the different degrees of flow resistance encountered by the nozzle holes. The lower layered nozzle holes encountered relatively less flow resistance than the upper layered ones. This result validates the experiment results obtained from the same nozzle, where the mean fuel injection quantities from eight fuel tunnels connected to the holes, showed the same trend.

## 1. Introduction

The performance and emission characteristics of diesel engines are largely governed by fuel atomization and spray processes which in turn are strongly influenced by the internal flow dynamics of injection nozzles [1–3]. With stringent emission regulations and increasing demand for fuel economy, injectors have become one of the most important parts of fuel injection system in diesel engines [4–6]. For a multihole injector, differences in injection rates between individual injection nozzle holes, result in non-uniform fuel distribution in space and time during spray combustion and therefore affect combustion quality and emission characteristics of diesel engines [7–9].

Bosch method [10–13] and Zeuch method [14–16] are currently two of the most common methods used to determine the instantaneous mass flow through diesel injectors. However, Charge measuring method [17] and Laser Doppler Anemometer [18] can also be used for fuel injection rate measurements. Although all of the above measuring methods are used to determine the total injection rate from multihole diesel injectors, they cannot be used to estimate hole-to-hole differences of a multi-hole nozzle. In this regard, the development of a hole-to-hole injection rate measuring system, will be immensely significant since it could serve as a guide for the optimization of multihole injectors during manufacturing [11]. Even though the deformation test method developed by Marčič et al. [7] and mass flow rate test bench constructed by Payri et al. [19] are used to determine the injection rate of nozzle holes from a multihole injector, they can only acquire data from one hole at a time. This present some limitations since data from each hole has to be acquired one at time before hole-to-hole characteristics could be analyzed, or results obtained from a single hole could be assumed to be the same with the other nozzle hole (in the case of symmetric multi-hole nozzles). However research have shown that, even in symmetric multi-holes, hole-to-hole injection rate are not the same due off-axis needle displacement, geometrical differences and internal flow characteristic difference.

A transient measuring test rig, which uses the principles of spray momentum flux theorem [20–24], was used to study the behavior and stability of injection from each nozzle hole, simultaneously [1]. The experimental test rig that was used for the simultaneous data

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**Nomenclature**

| | |
|---|---|
| $A_{geo}$ | geometrical outlet section ($m^2$) |
| $C_d$ | discharge coefficient |
| $C_n$ | non-uniform coefficient |
| F | spray impact force (N) |
| L | Nozzle exit and sensor surface distance (m) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $\dot{M}$ | spray momentum flux (kgm/s) |
| $n$ | injection pump speed (rpm) |
| $Q$ | cycle fuel injection quantity ($m^3$) |
| $t$ | time (s) |
| $t'$ | time delay (s) |
| $u$ | Velocity (m/s) |
| $\Delta P$ | Pressure drop (Pa) |
| $\Delta_1$ | relative difference between $Q_{below}$ and $Q_{upper}$ |
| $\Delta v_m$ | Mean velocity difference(m/s) |
| $\rho_f$ | Fuel density ($kg/m^3$) |
| $\Delta$ | Relative error |

*Subscript*

| | |
|---|---|
| $m$ | mean |
| $th$ | theoretical |
| $below$ | Lower layer |
| $upper$ | Upper layer |
| max | maximum |
| min | minimum |
| $\boldsymbol{f}$ | liquid |

acquisition, was developed and validated with experimental results from other experimental method. After the validation, the test rig was used to acquire and analyze the hole-to-hole injection rate differences from a double layered eight hole nozzle, at various operating conditions.

In this paper, the theory governing the measuring principle and the experimental setup, are described in Sections 2 and 3 respectively. The results, are presented in Section 4 and a summary conclusion in section 5.

## 2. Theoretical background and experiment

Employing the law of conservation of mass and momentum at the exits of the holes [21,25], together with the Bernoulli's theorem [26], the injection rate ($\dot{V}_b$) expression in Eq. (1) was obtained

$$\dot{V}_b = \sqrt{\frac{\dot{M} A_{geo} C_a}{\rho_f}} \tag{1}$$

where ($\dot{M}$) is the momentum at the exits, $A_{geo}$ is the geometric area of the holes, $C_a$ is the area coefficient and $\rho_f$ is the fuel density.

From the spray momentum flux experiment, the momentum at the exits was obtained. The experiment was conducted by mounting piezoelectric force sensors, perpendicularly to the axial directions of the injected fuel from the various holes as shown in Fig. 1. The sensor were carefully positioned and orientated at a distance (L) that ensured that the fuel will not rebound after impact and also the effect of inertia forces were eliminated. More detailed description of the theory and the experiment procedure adopted in this study are presented in [22].

By ensuring that the effect of rebound velocity and inertia forces on the results were negligible, the momentum flux ($M(t)$) and the instantaneous injection rates at the exits ($\dot{V}_b$), were expressed as

$$M(t) = F(t + t') \tag{2}$$

$$\dot{V}_b = \sqrt{\frac{F(t + t') A_{geo} C_a}{\rho_f}} \tag{3}$$

Integrating Eq. (3) over the complete injection cycle, the cycle fuel injection quantity from each nozzle hole ($Q$) was obtained.

$$q = \int \sqrt{\frac{F(t + t') A_{geo} C_a}{\rho_f}}\, dt \tag{4}$$

$$Q = \sum q \tag{5}$$

### 2.1. Experimental method

The customized spray momentum flux experimental setup is shown in Fig. 2. Although the experimental approach used in this study and in [22] are the same, the fuel injection systems and the injectors analyzed, were different. In the study conducted by Luo et al. [22], 5 hole asymmetric injector, used mainly in off-road machinery was investigated, whereas in this study a 6 hole symmetric nozzle injector and an eight hole double layered asymmetric nozzle injector were investigated. In [22], validation of fuel injection rates from each hole was performed by comparing the cycle fuel injection quantity of each hole (obtained by integrating the instantaneous injection rates through a complete injection cycle) to measured total fuel injected from it. Whereas in this study, the validation of fuel injection rate from the 6 hole injector, was performed by comparing the sum of the hole-to-hole cycle fuel injection rates to the total fuel injection rate (measured with an EFS IFR-600 m) from all the holes. For the 8 hole injector, the validation was performed by comparing the cycle fuel injection quantity from each hole to those measured with eight specially designed fuel separators. That is eight fuel tunnels, connected to each hole of the nozzle, were used to collect and measure the mean fuel injection quantities from them.

A high-pressure common rail fuel injection system was used for fuel supply instead of a pump-line nozzle system.

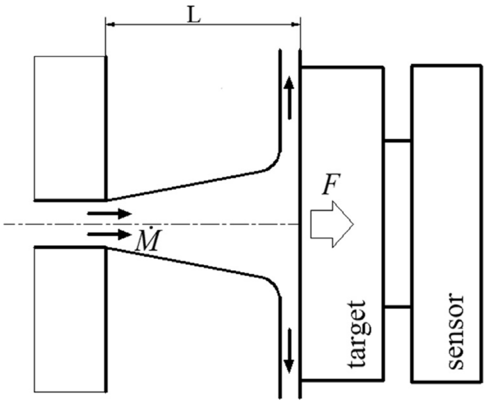

**Fig. 1.** Test principle of spray momentum flux.