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Measurements and analyses on the transient discharge coefficient of each nozzle hole of multi-hole diesel injector

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ABSTRACT

The objective of this paper is to propose a measuring method based on the spray momentum flux measurement of each nozzle hole that could be used to determine the transient discharge coefficient of each nozzle hole of a multi-hole diesel injector. For this purpose, a measurement system for the transient discharge coefficient of each nozzle hole was established utilizing a conventional injection system of pump-line-nozzle and a dedicated constructed experimental rig. By measuring the spray momentum flux of each nozzle hole of the multi-hole fuel injector and injection pressure of the pump-pipe-injector fuel delivery system, the discharge coefficient of each nozzle hole was obtained, and analyzed throughout the injection duration and with different injection pump speeds and cycle fuel injection quantities. The results show that the transient discharge coefficient of each nozzle hole changes constantly, meanwhile, the variations of the transient discharge coefficient of the nozzle holes were similar. However, the discharge coefficient of the nozzle holes were not uniform at the same operating condition and that of the No.5 was apparently lower than that of the others. With increasing cam speed, the fluctuations of the discharge coefficients were variably stable at the maximum needle position.The fluctuations of the discharge coefficients of the nozzle holes were higher for the smaller cycle fuel injection quantity, but as the fluctuation gradually became smaller, the mean discharge coefficient of each nozzle hole increased slightly with increasing cycle fuel injection quantity.

1. Introduction

With an increase in global concern in the effects of vehicular emissions on the environment (greenhouse effect of CO_2), the operations of the fuel injection system of diesel engines are of high importance. The injection nozzle and its components are the key elements affecting the air-fuel mixing process of diesel engine [1,2], since the combustion efficiency and pollutant formations are products of spray atomization and air-fuel mixing process [3–6].

The discharge coefficient is an important performance indicator of the injection nozzle and an index to evaluate the quality of the nozzle. Similarly, the transient discharge coefficient can reflect the actual dynamic variations taking place in the nozzle [7]. It is with this importance that the study and understanding of a measuring method by which the transient discharge coefficient can be accurately determined is paramount.

In order to enhance air-fuel mixing inside the combustion chamber of diesel engines, most of the engines are equipped with multi-hole injection nozzles [8]. Many methods and techniques have been developed [9–20], which gives reliable discharge coefficient measurements. Currently, all the measuring methods can give accurate results of the discharge coefficient in a single-hole nozzle injection system and other transients that exist during injection process [21–23]. Although more researchers have deduced various techniques in obtaining the transient discharge coefficients of each nozzle hole of a multi-hole injection nozzle, none analyses the possible differences in the discharge coefficient between individual holes of the nozzle [24].

Generally, the discharge coefficient of an injection nozzle refers to the value calculated by the injection quantity measured in steady state conditions [21,25,26]. Nevertheless, fuel flows inside injection nozzles are unsteady during fuel injection process due to inconsistencies within each nozzle hole of the diesel injector as a result of

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Nomenclature

A_{eff}	Effective outlet section
A_{geo}	Geometrical outlet section
A_0	Cross sectional area
C_a	Area coefficient
C_d	Discharge coefficient
C_v	Velocity coefficient
F	Spray impact force
L	The distance between the outlet and the target
$\dot{M}$	Momentum flux
$\dot{m}$	Mass flow rate
n	Injection pump speed
P_{inj}	Injection pressure
P_{back}	Backpressure
Q	Cycle fuel injection quantity of the measured injector
t	Time t
u	Real velocity
u_{eff}	Effective velocity
u_{th}	Theoretical velocity

Greek symbols

ΔP	Pressure drop
τ	Response time
ρ	Real density
$\rho_{N,T}$	Liquid fuel density under normal atmosphere and fuel temperature of t

manufacturing error, hence leading to differences in the discharge coefficients of the nozzle holes [27,28]. Therefore accurately measuring the transient discharge coefficient of each nozzle hole of a diesel injector is of high significance.

In our previous studies, the transient injection rates of each nozzle hole under different operating conditions were successively determined based on the measured spray momentum flux of each nozzle hole and the result shows that there were differences in the transient injection rates. The cause of these differences is yet to be studied or researched [29].

Per the objective of this research, the differences in discharge coefficients among nozzle holes of a multi-hole diesel injector can be obtained by evaluating the transient measuring method based on the law of conservation of momentum and momentum theorem. This will be realized by calculating the discharge coefficient of each nozzle of the injection system (by measuring their spray momentum flux and the injection pressure of the pump-pipe-injector fuel delivery system) and analyzing the differences in spray momentum flux, injection rate and discharge coefficient of the nozzle holes. Besides, the effect of injection pump speed and cycle fuel injection quantity on the discharge coefficient of each nozzle will be considered.

This paper is structured into these sections. Section 2 summarizes the theoretical background of the derivation of the formulae for the transient discharge coefficients of the injection nozzles. In Section 3, the proposed transient measuring method based on the law of conservation of momentum and momentum theorem and the experimental setup are described, while the analysis of the experimental results are carried out in Section 4. Finally, the relevant conclusions are presented in Section 5.

2. Theoretical background

The discharge coefficient (C_d) is defined as the ratio of the actual flow to the theoretical flow [3,7,26]. In complex flow conditions, the determination of the discharge coefficient at the nozzle exit is a difficult task as reported in various literatures [20,21,25,30,31]. A simplified approach described by Payri et al. [32] is used to analyze the challenging task of measuring the discharge coefficient at the injection nozzle exit and this is shown schematically in Fig. 1. From the figure, the spray impact force on each sensor surface is indirectly used to measure the transient spray momentum flux of each nozzle hole. With constant chamber pressure and perpendicular fuel deflections in the axial direction, as long as the area of the target sensor perpendicular to the spray axis is larger than the spray impact area, the force measured by the sensor is equal to the spray momentum flux at the outlet of the nozzle hole or at any other axial position [4,7,20,21].

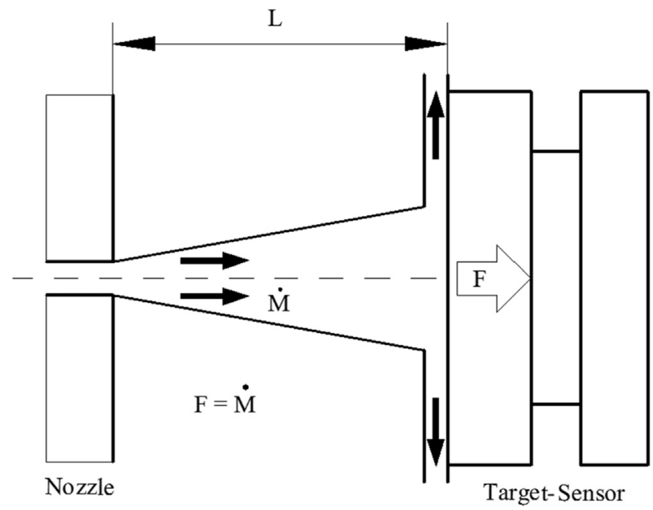

Fig. 1. Measuring method of the spray momentum flux.

Simply, the rebound velocity of spray particle after collision is assumed to be negligible during the spray-sensor collision [7], therefore from the law of conservation of momentum and the momentum theorem, the relationship between spray momentum and the corresponding impact force is expressed as:

$$F(t+\tau)=\dot{M}(t)+\dot{M}(\tau) \quad (1)$$

where $\dot{M}(t)$ is the transient spray momentum flux measured at the nozzle exit, $F(t+\tau)$ is the force measured by the sensor and $\dot{M}(\tau)$ represents the momentum flux of the inertia forces at the control volume (between the nozzle exit and the sensor surface) during the response time delay τ.

τ is expressed in seconds as:

$$\tau=\frac{L}{\sqrt{2\Delta \mathrm{P(t)}/\rho(\mathrm{t})}} \quad (2)$$

where L is the distance from the nozzle exit to the target sensor surface, $\Delta P(t)$ is the pressure difference $\left(\Delta P=P_{inj}-P_{back}\right)$ at time t, and ρ the fuel density.

With the existence of a control volume between the nozzle exit and the surface of the target sensor (cv) and per the analysis in [32], $\dot{M}(\tau)$ can be expressed as:

$$\dot{M}(\tau)=\frac{d}{dt}\int_{cv}u\rho dV \quad (3)$$

where u and ρ are the velocity and density at the control volume. Eq. (1) above was used in analyzing the spray momentum flux at both quasi steady state and transient stages respectfully. During the quasi steady state conditions, the inertia forces are negligible; therefore the force measured $F(t+\tau)$ at the sensor surface is equal to the momentum flux $\dot{M}(\tau)$ at the nozzle exit. In Ref. [29], time