

Characterization of Internal Flow and Spray Behaviors of Hole-Type Nozzle under Tiny and Normal Injection Quantity Conditions for Diesel Engine

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ABSTRACT

The tiny and normal injection quantity instances usually happen under the multi-injection strategy condition to restrain the uncontrollability of the ignition timing of the homogeneous charge compression ignition (HCCI) combustion concept. Meanwhile, instead of the traditional and fundamental single-hole diesel injector, the axisymmetric multi-hole injectors are usually applied to couple with the combustion chamber under most practical operating conditions. In the current paper, the internal flow and spray characteristics generated by single-hole and multi-hole (10 holes) nozzles under normal (2 mm³/hole) and tiny (0.3 mm³/hole) injection quantity conditions were investigated in conjunction with a series of experimental and computational methods. High-speed video observation was conducted at 10000 and 100000 fps under the condition of 120 MPa rail pressure, 1.5 MPa ambient pressure, room temperature, and nitrogen environment to visualize different spray properties. Moreover, the CFD calculation was also conducted under the same condition to reproduce the internal flow patterns inside different nozzles, which provided material for additional discussion and explanations for the mechanisms behind the spray behaviors. It revealed that the multi-hole nozzle had lower sac pressure and injection rate, longer injection duration, shorter spray tip penetration, and wider spray angle and spray cone angle compared to those of the single-hole nozzle. Meanwhile, the simulation study predicted that the internal flow patterns inside the multi-hole nozzle had more complicated vortex and turbulence structure and higher level of cavitation than the single-hole one. However, under different injection quantity conditions, the difference in the internal flow and spray behaviors between the single-hole and multi-hole nozzles presented distinctly different properties. It was concluded that the effect of the injection quantity plays different roles in the internal flow and near-field spray properties of the nozzles with distinct geometry and structure.

CITATION: Dong, P., Nishida, K., Inaba, T., and Ogata, Y., "Characterization of Internal Flow and Spray Behaviors of Hole-Type Nozzle under Tiny and Normal Injection Quantity Conditions for Diesel Engine," *SAE Int. J. Fuels Lubr.* 9(1):2016, doi:10.4271/2016-01-0862.

INTRODUCTION

The combustion process, emission formation, and the resulting engine performance in Diesel engines are well known to be governed mainly by the spray behaviors and the consequent mixture formation quality [1]. One of the most important factors that affect the spray development is the nozzle configuration, which can generate the absolutely different internal flow inside the nozzles. Originally, the single-hole Diesel injector is usually applied in fundamental research to provide insights into the spray characteristics. However, the spray emerging from a realistic multi-hole nozzle approaches the practical engine operation situation better. Therefore, the spray behaviors injected by the practical multi-hole nozzle is worthwhile to be investigated.

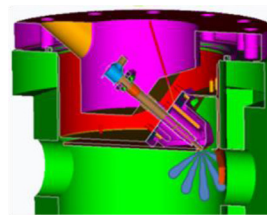
Furthermore, as one of the most ideal combustion models, homogeneous charge compression ignition (HCCI) has been drawing adequate attentions of the engine scholars for several years [2]. However, the traditional Diesel engines, which adopt high compression ratio to achieve the high power output, are mainly

responsible for the present difficulties in the realization of HCCI. Although decreasing the compressure ratio or making it variable is prevalent in achieving the ideal HCCI combustion conditions, it is still difficult to get the stable combustion instances inside Diesel engines with lower compressure ratio under the cold start and ideal mode conditions [3]. As a result, the multi-pilot injection strategy [4] is employed under these conditions to restrain the uncontrollability of the ignition timing, which inevitably introduces the tiny and normal injection quantity situations during the pilot and multiple injections.

To provide deep insights into the spray characteristics of the multi-hole nozzles applied under the realistic operation and different injection quantity conditions, the present investigation systematically made a comparison between the properties of the spray injected from a straight single-hole nozzle and those from an axisymmetric multi-hole nozzle with 10 holes. In addition, the CFD computation for these different nozzle configurations was also conducted to reproduce the internal flow and fuel spray transients under tiny and normal injection quantity conditions.

EXPERIMENTAL EQUIPMENT

In the current study, high-speed video observation experiments were performed using the single-hole and multi-hole injectors to observe the spray development processes, and the specific experimental apparatus are shown in Figure 1. Figure 1-(a) presents the global experimental arrangement, including a high-pressure chamber, injection system, and optical system. The working processes of this experimental system is described as follows: Diesel fuel was injected into the high-pressure constant volume vessel by the common rail injection system assembling different types of injectors, which could generate the injection pressure up to 200MPa. Transparent quartz windows were employed to make the inside optically accessible. The injection signal, fuel quantity, and image timing were controlled by an electronic control unit (ECU) and a delay pulse generator (Stanford Inc., DG535). The optical system consisted of a xenon lamp (USHIO Corp., SX-UID501XAMQ), two reflection mirrors, and two high-speed video cameras (Photron FASTCAM-APX RS and Nac MEMRECAM HX-3). The xenon lamp could emit continuous and high intensity light, and the incident light was reflected by the two mirrors. In this way, the two beams could be concentrated on the spray area through the quartz window, where the strong and uniform light intensity for spray scattering could be achieved.



c. Installation of multi-hole nozzle

Figure 1. (cont.) Experimental apparatus

When it comes to the installation of different injectors, in the case of the single-hole injector, the method of nozzle installation is shown in Figure 1-(b). It is well known that the observation of the multi-hole nozzle spray is difficult due to the conical structure formed by the sprays. In this study, to prevent spray interference, the multi-hole injector was installed into a specialized chamber cover obliquely, as shown in Figure 1-(c). There was an appropriate angle between the axis of the multi-hole nozzle and the horizontal plane, which could maintain one of the spray plumes to be observed as vertically as possible.

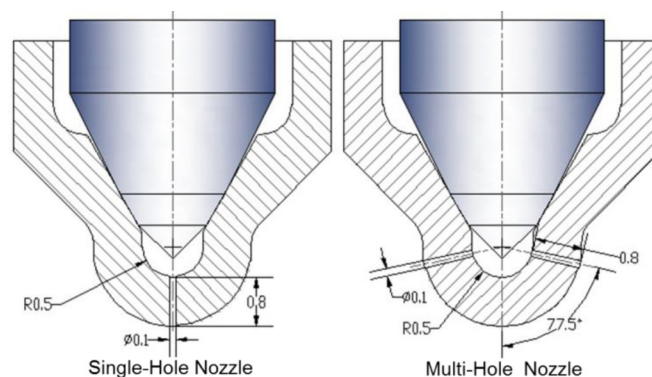
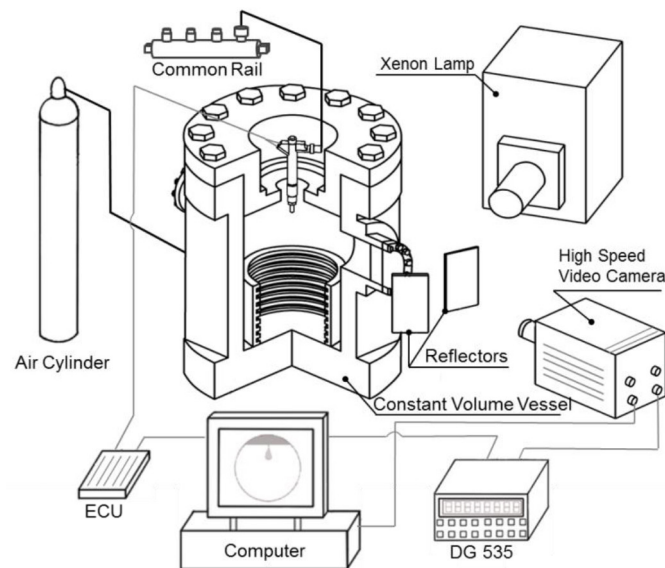


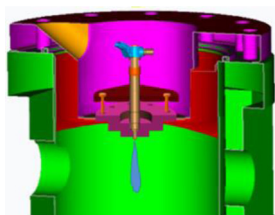
Figure 2. Schematic of different nozzles applied in the experiments

Figure 2 shows the typical scheme of the single-hole and multi-hole nozzles (with 10 holes) used in this study, and the specific nozzle parameters are also presented in this figure. Both of the two nozzles have the same sac radius, hole length, and hole diameter.

The experimental conditions, which are shown in detail in Table 1, were determined in consideration of the real operation conditions of small diesel engines. JIS #2 diesel was select as the test fuel. The injection quantity was kept as 0.3 mm³/hole and 2 mm³/hole to simulate the multi-injection instances in real Diesel engines. The injection pressure was selected as 120 MPa, while the ambient pressure and temperature for fundamental spray research were selected as 1.5 MPa and 300 K, respectively, which could keep the ambient gas density similar to that of the combustion conditions.



a. High-pressure chamber, injection system and optical system



b. Installation of single-hole nozzle

Figure 1.

Table 1. Experimental conditions

Injection Conditions				
Fuel	Diesel JIS#2			
Rail Pressure: P_{inj} (MPa)	120		120	
Injection Quantity: Q_{inj} (mm ³ /hole)	0.3		2.0	
Injector	Single-hole/ Multi-hole		Single-hole/ Multi-hole	
Injection Duration: Δt_{inj} (ms)	0.17	0.24	0.64	0.84
Ambient Condition				
Ambient Gas	Nitrogen			
Ambient Pressure : P_a (MPa)	1.5			
Ambient Temperature : T_a (K)	300			
Ambient Density : ρ_a (kg/m ³)	17.4			

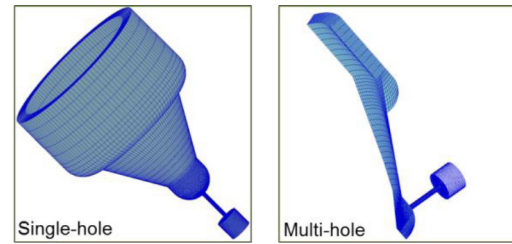
Moreover, the BOCSH long tube meter [5] was selected as the instrument to measure the rate of injection of the nozzles under the same conditions with the Mie-scattering experiments, and each measurement was conducted at least 10 times to exclude the hole to hole and spray to spray variation, especially under the tiny injection quantity condition.

SETTING OF THE COMPUTATIONAL STUDY

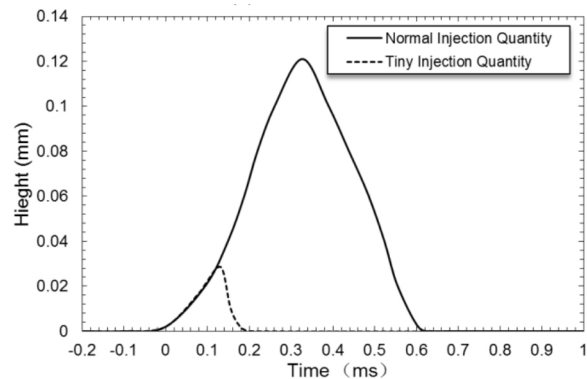
With the development of the numerical simulation techniques, it has launched a new era for researchers to investigate the internal flow in real-size nozzles under realistic operating conditions. In the current study, the internal flow and cavitation characteristics generated by different nozzle geometric structure under different injection quantity conditions have been numerically reproduced by the commercial CFD Code-Fire Version 2013 (AVL). The unsteady multi-phase flow inside the nozzle was predicted using two-fluid model.

The computational meshes for nozzles with different structures are shown in Figure 3. As for the multi-hole nozzle with ten holes, considering the geometric periodicity, symmetry, and calculation timing, only one-tenth of the whole volumetric domain was selected. The additional discharge volume could be used to avoid the countercurrent from the outlet around the start of injection, and could also be used to observe the near field spray transient. As shown in the same figure, the needle movement is taken into account in the meshing process, and two needle lift curves, which represent the tiny and normal injection quantity conditions, were applied to reproduce the hydrodynamic instances inside the nozzle geometry. These curves were measured from a similar type of multi-hole injector used in the current experiment. For one injection quantity condition, the same curve was applied for the single-hole and multi-hole nozzles simultaneously to make comparison between the internal flow patterns inside different nozzle geometric structures.

In this way, different injection stages (initial, middle, and post stages), and different needle position conditions (low and high needle lift) could be simulated to explain the spray behaviors and properties observed in the experiments.



a. Calculation Meshes



b. Needle lift curve applied in the calculation

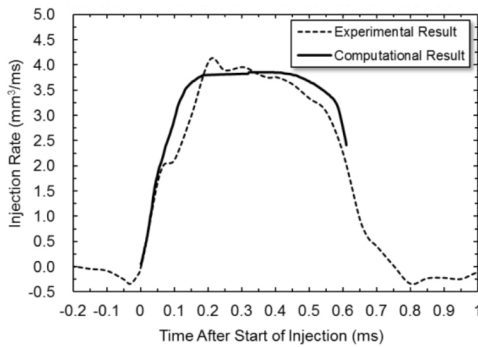
Figure 3. Computational meshes and needle lift curves

The specific setting for this computation has been listed in Table 2. The Reynolds Averaged Navier-Stokes Simulation (RANS) method, multi-phase flow model, and a four-equation k- ζ -f turbulent model [6], based on the Durbin's elliptic relaxation concept [7], were adopted to simulate the fluid inside the nozzle. Furthermore, the Linearized Rayleigh model was used to express the cavitation bubble behaviors within the nozzle. Before the further simulation, validation was made on the adopted turbulent and cavitation models. The result is shown in Figure 4.

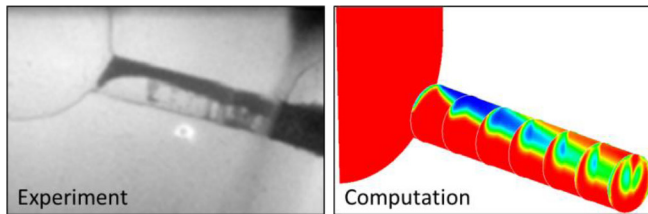
Table 2. Computation setting

Item	Classification	Value
Physical properties	Density (kg/m ³)	830
	Viscosity (N·s/m ²)	0.00214
	Temperature (K)	293.15
	Second phase Density (kg/m ³)	7
	(Diesel phase) Viscosity (N·s/m ²)	10 ⁻⁵
Initial boundary	Inlet boundary	Injection Pressure (MPa)
	Outlet boundary	Ambient Pressure (MPa)
K- ζ -F		
Model selection and	Turbulence model	Turbulence energy (m ² /s ²)
		Turbulence length scale (m)
Initial values	Linear cavitation model	
	Cavitation model	Cavitation bubble density number
		Saturated vapor pressure (Pa)
Mesh information	Total grid number	Single-hole nozzle
		Multi-hole nozzle
	The minimum size	In the hole region (mm)





a. Injection rate results from the experiment and computation



b. Cavitation results from the experiment and computation

Figure 4. Validation of the computation setting

The experimental results from the paper published by Blessing et al. [8] have been taken as criterions for the validation, because the characteristics of the injector and experimental conditions in their work covered some feature of the current investigation. The grid size (2.5 and 4.41 μm) effect on the result was also tested before the further simulation study. As shown in Figure 4, during the verification process, it had been proved that both the mass flow rate and the distribution and occurrence of the cavitation could be predicted accurately relatively by this simulation.

RESULTS AND DISCUSSIONS

Experimental Results

In this section, the injection processes and near-field spray properties of single-hole and multi-hole nozzles under tiny and normal injection quantity conditions will be concentrated on, and two kinds of comparison will be made to investigate that (1) under the same nozzle configuration conditions, the difference in the injection processes and spray characteristics between the tiny and normal injection quantity strategies; (2) under the same injection quantity condition, the difference in the injection processes and spray characteristics between the single-hole and multi-hole injectors.

The injection rate results measured by the BOCOSH long tube method is shown in Figure 5. For the single-hole nozzle, there are fluctuations under both tiny and normal injection quantity conditions, especially

under the tiny one. It seems that there is pressure oscillation inside the sac of the single-hole nozzle, and the needle movement is a little nonlinear [9]. The water hammer effect caused by the limited effective flow area (single-hole) and the super short energizing duration may contribute to this issue. On the contrary, for the multi-hole nozzle, the injection rate curves are all smooth under different injection quantity conditions, and the trend of the two curves changes placidly with the time after start of injection. This is attributed to the lower increasing rate of the sac pressure caused by the large fuel flow area (10 holes) and the relatively longer energizing period of the injection signal.

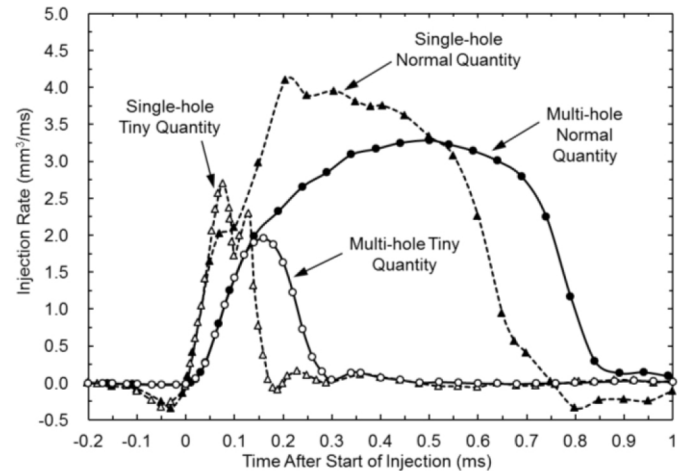


Figure 5. Injection rate results under different injection quantity conditions

From another view, no matter under tiny or normal injection quantity condition, it is obvious that the injection rate of the single-hole nozzle is higher than that of the multi-hole nozzle, especially at the initial stage of injection. However, the injection duration of the single-hole nozzle is shorter than that of the multi-hole nozzle when maintaining the same injection quantity per hole. Compared with the tiny injection quantity condition, the difference in the injection rate and injection duration between the single-hole and multi-hole nozzles is larger under the normal injection quantity condition. The following discussion will give deeper analysis about the phenomenon described above.

The typical false-coloured and temporal spray images under different injection quantity conditions, which are converted from the black-white images, are shown in Figure 6. It is known that the illumination light intensity and the spray contours are symbolic characteristics of the fuel droplet size, concentration, the effects of ambient gas entrainment, and interactions between spray plumes [10].

Affected by the different injection duration, the selection of the typical timings for different injection quantity conditions is a little different. Comparing the spray developing from different nozzles