

Theoretical Study on Spray Design for Small-Bore Diesel Engine (Second Report)

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ABSTRACT

Generally, soot emissions increase in diesel engines with smaller bore sizes due to larger spray impingement on the cavity wall at a constant specific output power. The objective of this study is to clarify the constraints for engine/nozzle specifications and injection conditions to achieve the same combustion characteristics (such as heat release rate and emissions) in diesel engines with different bore sizes. The first report applied the geometrical similarity concept to two engines with different bore sizes and similar piston cavity shapes. The smaller engine emitted more smoke because air entrainment decreases due to the narrower spray angle. A new spray design method called spray characteristics similarity was proposed to suppress soot emissions. However, a smaller nozzle diameter and a larger number of nozzle holes are required to maintain the same spray characteristics (such as specific air-entrainment and penetration) when the bore size decreases. This second report proposes another approach that maintains the same nozzle diameter and number of nozzle holes. When the similarity ratio is defined as the ratio of the bore diameter between a targeted engine and the base engine, this new method (called the "geometric similarity of fuel spray" concept) can be expressed as functions of the spray penetration, spray angle, and excess air ratio. This method requires the fuel spray angle to be the same regardless of the engine size. To achieve this condition, a newly designed step shaped nozzle was adopted to increase the fuel spray angle compared to a conventional straight hole nozzle. In the case of the geometric similarity of fuel spray concept, soot emissions are the same as those generated by a longer nozzle, while maintaining the same spray angle as the conventional straight nozzle. Consequently, it was confirmed experimentally that theoretical solutions based on the geometric similarity of fuel spray concept can obtain almost constant soot emissions in different sized engines.

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1. INTRODUCTION

Although smaller diesel passenger vehicles and downsized diesel engines are being developed to further lower CO₂ emissions, the adoption of smaller engine bore sizes generally makes emissions regulations more difficult to satisfy [1][2]. This is because a smaller bore size reduces the size of the combustion chamber, thereby inhibiting the propagation of the fuel spray and increasing the number of rich areas. In contrast, if a generalized combustion process that does not depend on the diameter of the bore (i.e., similar combustion) can be realized, it should be possible to carry out parallel development of multiple engines with different sizes to meet various power requirements. This would have the effect of greatly consolidating the engine development process. Chikahisa et al. proposed a geometrical similarity theory concept applicable to engines with different bore sizes [3][4][5][6]. However, these studies involved simple investigations into macro-based similarities such as the heat release rate and mixture distribution. 3D-CFD analysis added the new idea of flame lift scaling to the similarity theory. The idea of an extended scaling model enables to predict the combustion

characteristics more closely [7][8][9][10]. Experimental validations were also conducted using two different sizes engines. There were some differences in particulate matter (PM) and initial heat release rate between two engines [11]. Therefore, more detailed theoretical and experimental studies are necessary to control both macro-combustion characteristics, as well as NO_x and smoke emissions which are crucially sensitive to local gas mixture conditions.

The aim of this research is to identify the necessary conditions to equalize emissions performance as well as the heat release rate for two engines with different bore sizes. The first report described a case in which the combustion chamber geometry and nozzle hole specifications were reduced based on the similarity ratio (Figure 1, referred to below as "geometrical similarity"). Although the smaller bore engine achieved the same heat release rate (when normalized by the injection quantity) as the larger bore engine, NO_x-smoke characteristics deteriorated [12]. Subsequently, the causes of this deterioration were identified theoretically by generalizing the geometrical similarity of the spray characteristics using physical

formulas. In addition, a similarity theory for spray characteristics was constructed to equalize the heat release rate and emissions performance by reviewing the preconditions. This theory showed that equalization could be achieved by adopting a nozzle with a larger number of smaller holes.

To avoid higher system costs caused by design restrictions due to the use of smaller nozzle holes, this second report identifies the required conditions to achieve similar characteristics per nozzle hole, while maintaining the diameter and number of the nozzle holes (this concept is referred to below as the "geometrical similarity of the spray"). The aim of this approach is to equalize the heat release rate and emissions performance by revising the nozzle hole geometry.

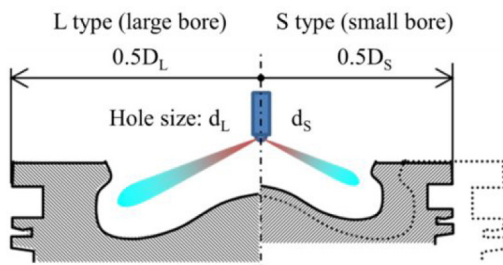


Figure 1. Geometrical similarity of spray-combustion system.

2. EXPERIMENTAL APPARATUS AND METHOD

An evaluation was carried out using spray visualization equipment and single-cylinder engines with different bore diameters to verify the similarity of spray characteristics, heat release rate, and emissions characteristics. This evaluation used the test apparatus described below.

2.1. Spray Observation Device under Non-Evaporative Conditions

The spray observation device described in the first report was used to measure typical spray characteristics (spray cone angle and spray tip penetration) [12]. In addition, the fuel density distribution of the sprays was measured using laser induced fluorescence (LIF) and compared. Figure 2 shows the optical setup. It uses the 4th harmonic of a Nd:YAG laser to illuminate the section that passes through the spray axis. Images were taken using an intensified charge-coupled device (ICCD) camera.

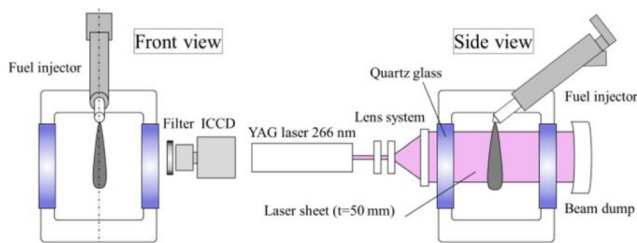


Figure 2. Optical setup for LIF measurements of fuel.

2.2. Visualization of Burning Spray Using Rapid Compression Machine

The burning spray was visualized using an optically accessible rapid compression machine (RCM) [13][14] to observe the combustion characteristics. The Schematic overview of rapid compression machine is shown in Figure 3, and the experimental conditions are listed in Table 1. High temperature and high pressure conditions are created when a cam linked to an air cylinder is rapidly driven using compressed air, and the curved surface of the cam drives the piston, which compresses the in-cylinder air in the combustion chamber and makes it flow [14]. The RCM combustion chamber has a cylinder 20mm height with a diameter of 50mm, and differs from an actual engine with cavity. Also, there is no expansion stroke, and the in-cylinder flow behavior differs from that of an actual engine. However, the RCM has a quartz observation window so it is easy to capture entire combustion chamber with spray and combustion behavior.

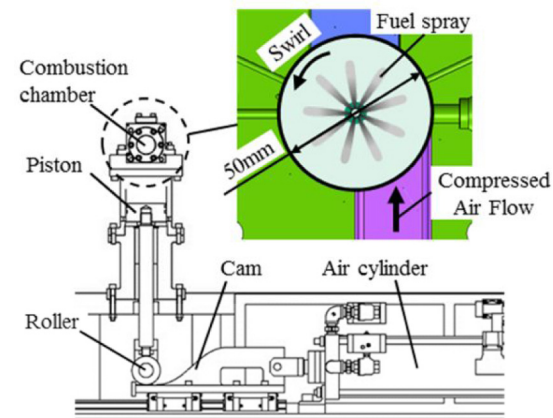


Figure 3. Schematic overview of rapid compression machine.

Table 1. Experimental conditions of rapid compression machine.

Ambient pressure [MPa]	6.0
Ambient temperature [K]	900
Swirl ratio	2.0

The burning spray was visualized using the shadowgraph method. Parallel light generated by a convex lens from a halogen lamp was introduced into the chamber through a half-mirror and illuminated the spray. Light reflected from a chromium-plated mirror behind the spray was collected by a high speed CMOS camera (Vision Research Phantom V7.3) operating at 36,000fps. The source of the parallel light for the shadowgraph imaging was a halogen lamp. Besides, a direct photograph method was used to visualize the luminous flame behavior after ignition. Neutral density (ND) filters and the aperture of the lens were used to reduce the exposure for the luminosity imaging.

Figure 4 shows a typical pressure curve in the combustion chamber of RCM. When the piston compresses the air, the pressure immediately increased. At certain timing after the pressure peaks due to heat loss, diesel fuel was injected. The second pressure peak is due to the diesel combustion.

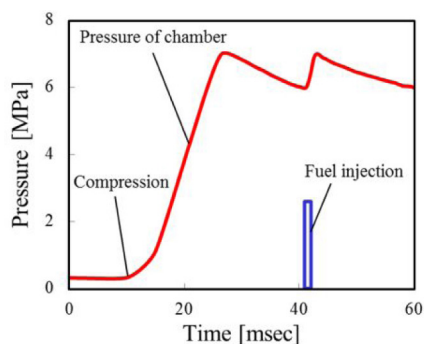


Figure 4. Compression and fuel injection timing with pressure history of rapid compression machine.

2.3. Test Engines

The similarity of the heat release rate, fuel efficiency, and emissions performance was evaluated using the same single-cylinder engines as described in the first report. Table 2 shows the basic specifications. The base large-bore (L type) engine has a bore diameter of 86 mm compared with 73 mm for the smaller bore (S type) engine. This is a similarity ratio r of 0.85. The engines were evaluated under high load operating conditions and, to verify the similarity within an applicable operating range, at full power. The high load and full power conditions are shown in Tables 3 and 4, respectively. Under each set of conditions, the heat release rate was calculated from the measured cylinder pressure, and the emissions were measured.

Table 2. S and L type engine specifications.

	S type/L type	Ratio (S/L)
Bore [mm]	73.0/86.0	$r=0.85$
Stroke [mm]	81.5/96.0	$r=0.85$
Compression ratio	15.8/15.8	1
Swirl ratio	1.8/1.8	1

Table 3. Operating conditions (high load).

	S type/L type	Ratio (S/L)
Targeted IMEP [MPa]	1.6/1.6	1
Engine speed [rpm]	2,000/2,000	1
Boost pressure (abs.) [kPa]	190/190	1
Intake gas temperature [°C]	40/40	1
Injection pressure [MPa]	130/180	r^2
Fuel amount [mm ³]	33.5/54.8	r^3
Injection timing [ATDC]	-0.5/-0.5	1
Coolant temperature [°C]	80/80	1
Lubricant temperature [°C]	80/80	1

Table 4. Operating conditions (full power).

	S type/L type	Ratio (S/ L)
Targeted IMEP [MPa]	2.1/2.1	1
Engine speed [rpm]	3,200/3,200	1
Boost pressure (abs.) [kPa]	225/225	1
Intake gas temperature [°C]	45/45	1
Injection pressure [MPa]	130/180	r^2
Fuel amount [mm ³]	45.8/74.6	r^3
Injection timing [ATDC]	-8.5/-8.5	1
Coolant temperature [°C]	80/80	1
Lubricant temperature [°C]	80/80	1

3. GEOMETRICAL SIMILARITY AND GEOMETRICAL SIMILARITY OF SPRAY

This section describes the geometrical similarity concept discussed in the first report and the approach that was constructed to help resolve the issues of this concept, called the geometrical similarity of the spray. It also covers the main items to be addressed in this research.

The geometrical similarity concept of the first report [12] can be explained using Equations (1) to (8).

$$\text{Bore diameter: } D_S/D_L = r \quad (1)$$

$$\text{Injection quantity: } m_{f,S}/m_{f,L} = r^3 \quad (2)$$

$$\text{Air density: } \rho_{a,S}/\rho_{a,L} = 1 \quad (3)$$

$$\text{Swirl: } SR_S/SR_L = 1 \quad (4)$$

$$\text{Nozzle hole diameter: } d_{n,S}/d_{n,L} = r \quad (5)$$

$$\text{Number of nozzle holes: } n_S/n_L = 1 \quad (6)$$

$$\text{Nozzle hole length: } l_n/d_n = \text{const.} \quad (7)$$

$$\text{Injection pressure: } \Delta P_{cr,S}/\Delta P_{cr,L} = r^2 \quad (8)$$

With similar nozzle hole dimensions, reducing the size of the bore is likely to cause a deterioration in emissions due to the difference in the spray characteristics. The causes of this deterioration were examined based on Wakuri momentum theory [15]. Equations (9) to (12) were derived by formularization using empirical formulas.