

Ignition and Combustion Characteristics of Wall-Impinging Sprays Injected by Group-Hole Nozzles for Direct-Injection Diesel Engines

Seoksu Moon, Jian Gao, Keiya Nishida and Yuhei Matsumoto
University of Hiroshima

Yuyin Zhang
Tokyo Denki University

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ABSTRACT

The concept of two closely spaced micro-orifices (group hole nozzle) has been studied as a promising technology for the reduction of soot emission from direct injection (DI) diesel engines by improving the fuel atomization and evaporation. One of the main issues on group hole nozzle is the arrangement of orifices with various distances and angles. In this study, the ignition and combustion characteristics of wall-impinging diesel sprays from group-hole nozzles were investigated with various angles between two micro-orifices (included angles). A laser absorption scattering (LAS) technique for non-axisymmetric sprays, developed based on a LAS technique for axisymmetric spray, was applied to investigate the liquid/vapor mass distribution of wall-impinging sprays. The direct flame images and OH radical images inside a high pressure constant volume vessel were captured to analyze the effect of included angle on spray ignition and combustion characteristics.

The group hole nozzles showed improved fuel evaporation and increased spray tip penetration compared to the conventional single hole nozzle. In group hole nozzles, the longer spray penetration after impingement was observed at parallel direction compared to the vertical direction and the same trend was observed in the flame geometry. The spray penetration in parallel direction was increased at high included angles while there was not so much change in vertical direction. The vapor mass concentration in both view directions was enhanced when the included angle was increased due to the reduced droplet collision region. Owing to the enhanced fuel evaporation, the ignition delay of wall-impinging sprays was shortened and the intensity of OH

chemiluminescence increased at high included angles. The shorter flame length and longer flame height were observed at high included angles since the ignition occurs before the spray-wall interaction is fully developed.

INTRODUCTION

Recently, the direct fuel injection in combination with the high-pressure injection systems has led to obvious improvement in the efficiency of modern diesel engines. Nevertheless, to meet forthcoming strict emission regulations for particulate matter (PM) and nitrogen oxides (NO_x), further development in engine design is required. Although there have been numerous endeavors for the reduction of engine-out emissions, the dominant technologies can be summarized as follows;

- Adoption of higher pressure injection system up to 200MPa
- Using the Piezo injection system with fast response
- Multiple injections
- Minimization of nozzle orifice diameter/Increase in orifice number
- Low temperature combustion (LTC) with cooled EGR system
- Variable geometry turbocharger (VGT)
- Lowering the compression ratio
- Aftertreatment system: diesel particulate filter (DPF), Lean-NO_x catalyst, De-NO_x catalyst, selective catalytic reduction (SCR)

Although the installation of the aftertreatment system is a current hot-issue on the engine production, the reduction of diesel engine emissions formed by the in-cylinder combustion is also of importance. To reduce the PM

emission from combustion, the fuel should meet the affluent oxidant by enhancing the atomization and evaporation of injected fuel and improving the spatial distribution of fuel and oxidant. To improve fuel evaporation, current researches focused on high pressure injection with micro-orifices [1, 2]. There have been many researches about the effect of orifice diameter and the results showed the increased ratio of entrained air mass to the injected fuel mass and longer flame lift-off length and, consequently, improved atomization and evaporation of injected fuel at smaller orifice diameters [1-7]. This enhanced atomization and evaporation at small orifice diameter caused less soot emission from engine combustion [2, 6, 7-9]. The previous researches revealed that the high injection pressure with micro-orifices can be effective in low and middle loads conditions [2, 6, 7-9]. Nevertheless, the shorter spray tip penetration from this technology can be a drawback in high speed and load conditions. The weakened interaction between fuel spray and piston cavity, caused by the shorter spray tip penetration, decreases the air utilization inside the piston cavity and finally increases the soot emission at high load and speed conditions [9, 10]. From these results, it can be concluded that the atomization characteristics and the spray tip penetration should be compromised for the optimized engine combustion.

The concept of group hole nozzle that equips the closely located two micro-orifices has been introduced to improve the atomization characteristics of spray compared with the conventional single hole nozzle spray without the decrease in spray tip penetration [11-13]. Figure 1 shows the conceptual diagram of group hole nozzle compared with the single hole nozzle. From the previous results, it was found that the group hole nozzle spray has some advantage in fuel evaporation without the sacrifice in spray tip penetration [12, 13]. The mass of fuel vapor and ratio of evaporation were enhanced compared with the single hole nozzle as the distance between two micro-orifices increased due to the less droplet collision/coalescence region, although the fuel evaporation was less than the spray from totally separated two micro hole nozzles. The spray penetration from group hole nozzle was similar with that from single hole nozzle, while it showed obviously longer spray penetration compared with the totally separated two micro-orifices. It designates that the group hole nozzle spray has the neutral characteristics between the single hole nozzle and totally separated two micro-orifices, although the improvement in fuel evaporation is relatively higher compared with the sacrifice in spray tip penetration.

Another possible advantage from group hole nozzle spray could arise from the impinged spray characteristics to the piston bowl. From the previous researches, it was found that the shape of spray after impingement injected by group nozzle was asymmetrical, thus the spray tip penetration is increased to a certain direction (upside and downside in Fig. 2) and decreased to another direction compared with the single hole nozzle spray [13]. From the deposit image of spray (left image in Fig. 2), the outward bulge was found and it confirmed above explanation. At

the moment of wall-impingement, the momentum interaction of two close jets results in a flow along a line, which vertically crosses a center point of a line connecting the centers of two circles [13], as shown in the right image of Fig. 2. This flow forms the bulges a result of the two sliding velocity components along the impingement surface in the overlapping area, which is presumably greater than that of the sole jet. Correspondingly, if the nozzle alignment is optimized to make the longer penetration region from the group hole nozzle spray head to central region of piston cavity, the air utilization inside the combustion chamber could be enhanced.

Although there were some researches which investigated the effect of the distance between two micro-orifices on mixture formation and in-cylinder combustion characteristics [13], the effect of included angles has not been under investigation. Subsequently, the aim of this research is to investigate the effect of the included angles on the mixture formation process of wall-impinging spray and combustion characteristics inside a high pressure vessel. The mixture formation process of wall-impinging spray was analyzed using a LAS technique for non-axisymmetric sprays, developed based on the technique for axisymmetric sprays. The methodology for LAS technology will be described in the following section. The direct flame and the OH chemiluminescence images of wall-impinging spray were captured inside a high pressure vessel to analyze the ignition delay, flame geometry, OH chemiluminescence intensity and spatial distribution of OH radical from spray combustion. OH chemiluminescence has been selected from previous researches for the determination of light-off length, since it was known to occur under high temperature and stoichiometric conditions and appear at the onset of combustion [14-16]. Furthermore, OH chemiluminescence inside the combustion chamber has been visualized from many researchers to inspect the possibility of soot oxidation because OH radical is a dominant soot oxidizer [17, 18]. In this research, the OH chemiluminescence images were used to expect the possible soot emission from group-hole nozzles at different included angles to judge the applicability of group-hole nozzles for the real engine combustion.

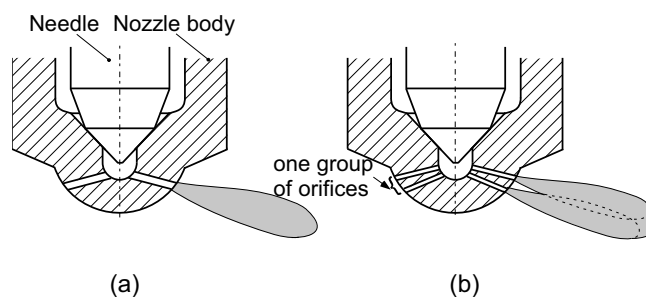


Fig. 1 Conceptual diagram of single hole nozzle and group hole nozzle [(a) Concept of single hole nozzle, (b) Concept of group hole nozzle]

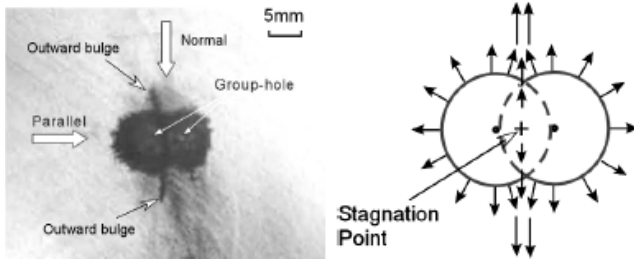


Fig. 2 The deposit generated from group hole nozzle spray (left) and theoretical diagram of fuel flow after impingement (right), taken from Ref. [13]

PRINCIPLE AND METHODOLOGY OF LAS TECHNIQUE FOR NON-AXISYMMETRIC SPRAYS

The principle of LAS technique for non-axisymmetric sprays was introduced from a reference [13]. Therefore, the principle and methodology of LAS technique for non-axisymmetric sprays were briefly summarized in this paper as below.

PRINCIPLE OF LAS TECHNIQUE FOR NON-AXISYMMETRIC SPRAY

Figure 3 shows the principle of LAS technique. The LAS technique was introduced and then developed by lots of previous researches [19-21]. An incident light with two wavelengths (λ_A : absorption wavelength, λ_T : transparent wavelength) transmits through the liquid and vapor phase of fuel inside the spray. The intensity of incident light (I_0) is attenuated to the intensity of transmitted light (I_t). The total line-of-sight extinction of the absorbing wavelength light is a result of droplets scattering, droplets absorption and vapor absorption (Eq. (1)). The extinction of the transparent wavelength light is only contributed by the droplets scattering (Eq. (2)).

$$\log\left(\frac{I_0}{I_t}\right)_{\lambda_A} = \log\left(\frac{I_0}{I_t}\right)_{Lsca+Labs} + \log\left(\frac{I_0}{I_t}\right)_{Vabs} \quad (1)$$

$$\log\left(\frac{I_0}{I_t}\right)_{\lambda_T} = \log\left(\frac{I_0}{I_t}\right)_{Lsca} \quad (2)$$

Therefore, if the extinction of both two wavelength lights by the liquid phase is the same, the line-of-sight vapor optical thickness can be obtained by removing the droplets optical thickness at the transparent wavelength from the optical thickness of vapor and droplets at the absorbing wavelength (Eqs. (3) and (4)).

$$\log\left(\frac{I_0}{I_t}\right)_{Vabs} = \log\left(\frac{I_0}{I_t}\right)_{\lambda_A} - \log\left(\frac{I_0}{I_t}\right)_{\lambda_T} \quad (3)$$

$$\log\left(\frac{I_0}{I_t}\right)_{Lsca} = \log\left(\frac{I_0}{I_t}\right)_{\lambda_T} \quad (4)$$

The vapor concentration will be then yielded through utilizing the onion-peeling model for the case of the axisymmetric spray, and liquid phase concentration can be attained from the droplets optical thickness with knowledge of the total liquid mass [19-21].

However, in case of non-axisymmetric spray, the onion-peeling model is not applicable. Therefore, new LAS technique, capable of measuring the accumulative mass and the mass distributions of vapor/liquid phases per unit projection area regardless of the spray shape, was developed. Based on the Lambert-Beer's law shown in Fig. 4, the vapor phase concentration (C_v) can be presented as Eq. (5).

$$\log\left(\frac{I}{I+dl}\right)_{Vabs} = \frac{\varepsilon}{MW} \cdot C_v \times 10^2 dl \quad (5)$$

where,

l : optical path length [m]

ε : molar absorption coefficient [l/mol·cm]

MW : mole weight [kg/kmol]

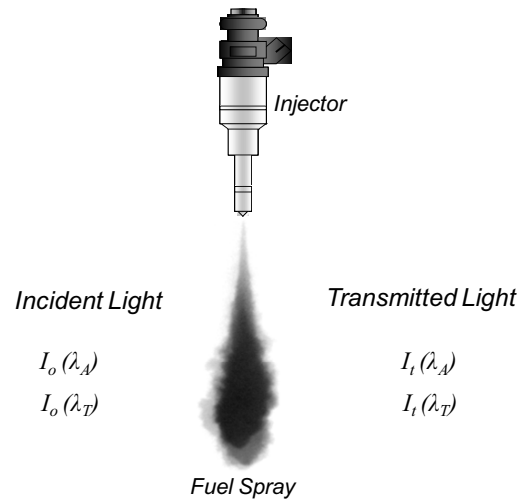


Fig. 3 Principle of LAS technique

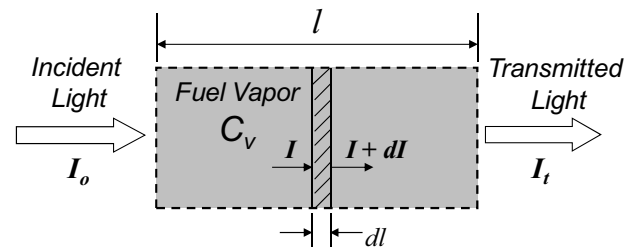


Fig. 4 Lambert-Beer's law

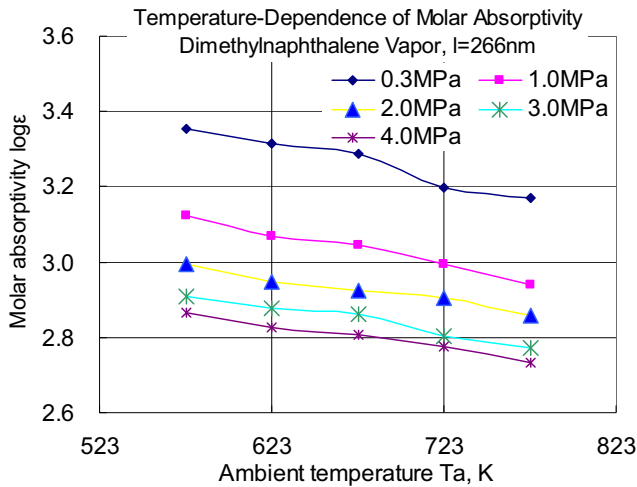


Fig. 5 Temperature dependence of molar absorption coefficient of DMN at different ambient pressures: ambient gas, nitrogen; wavelength λ , 266nm; optical path length L , 100mm

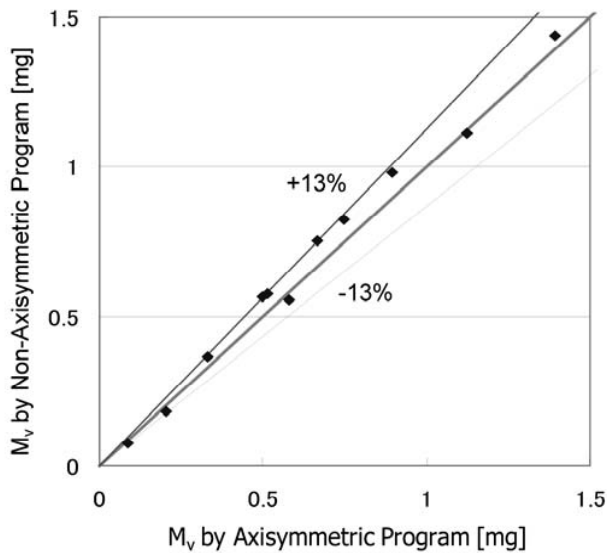


Fig. 6 Comparison of the results from axisymmetric program and non-axisymmetric program

Molar absorption coefficient depends on the temperature. Figure 5 shows the temperature dependency of molar absorption coefficient. To estimate the possible error in molar absorption coefficient, the temperature change in injection process was calculated using enthalpy conservation of fuel and ambient gas. The calculated possible temperature change in injection process was 40K and the estimated error range in ε was less than 2%. Assuming the constant molar absorption coefficient, the vapor concentration and vapor mass distribution can be expressed as Eqs. (6) and (7).

$$\overline{C_V} = \int_l C_V dl = \frac{MW}{\varepsilon} \int_l \log\left(\frac{I}{I + dI}\right)_{V_{abs}} dl$$

$$= \frac{MW \cdot \log(I_0/I_t)_{V_{abs}}}{\varepsilon} \quad (6)$$

$$M_V = \int_S \overline{C_V} dS = \int_S \frac{MW \cdot \log(I_0/I_t)}{\varepsilon} \times 10^{-2} dS \quad (7)$$

DETERMINATION OF TEST FUEL

The test fuel requirements for LAS technique were summarized by a previous study [19]. Most important requirement is that vapor phase of test fuel should have a strong absorption for ultraviolet light and be almost transparent for visible light. The 1,3 dimethylnaphthalene [$C_{10}H_6(CH_3)_2$] (abbreviated as 1,3-DMN) has been proved to strongly absorb light at 266nm but does not absorb light at 532nm [19] and the physical properties such as boiling point, viscosity and evaporating rate are similar to those of diesel fuel. Therefore, the 1,3-DMN was selected as test fuel in this study.

ERROR ANALYSIS

In case of the LAS technique for axisymmetric spray, estimated possible error from LAS technique was maximum 15% [20]. In this previous study, measurement accuracy of the LAS technique for axisymmetric spray was investigated by comparing the vapor mass of the completely evaporated spray measured by the LAS technique with the injected fuel mass measured by a sampling method. Figure 6 shows the difference in calculated vapor phase mass between axisymmetric program and non-axisymmetric program. Although there is maximum 13% difference in calculated results, the almost identical results was observed for each program. However, further investigation is required to obtain precise error from LAS technique for non-axisymmetric spray.

EXPERIMENTAL APPARATUS

SETUP FOR LAS TECHNIQUE

The LAS measurements were implemented in a high temperature and high pressure constant volume vessel. A schematic diagram of the optical arrangement of the LAS imaging system, the fuel injection system and the constant volume vessel is shown in Fig. 7. A pulsed Nd:YAG laser (NY61-10, Continuum) was employed to provide the two wavelength beams, one at ultraviolet (UV) 266nm (absorption wavelength) and the other at visible (Vis) 532nm (transparent wavelength). The two beams were separated by a dichroic mirror, and were magnified into a diameter of 100mm by the beam expanders. A reflection mirror and two harmonic mirrors made the two expanded beams coaxial again and traversed into the constant

volume vessel, transmitted the spray and were separated again on the other sides. In order to minimize the schlieren-like effect due to the ambient gas density gradient on the LAS image, a diffuser was set between the first harmonic mirror and the window of the vessel. Finally, the two beams were focused and captured by two CCD cameras (Photonics C4880, Hamamatsu, 384X576 pixels and 12bit grayscale).

Spectral filters and apertures in front of the CCD cameras cut off the optical noises beyond the incident wavelength and scattered light beyond the optical half angle respectively. The sizes of the apertures for UV and Visible beams were 10mm and 20mm respectively. The focal length and the diameter of the collimating lenses before the cameras were 500mm/150mm. The images acquisition and arithmetic processing were carried out by an IPLab (Spectrum Signal Analytics) mage analysis system. The laser pulse was triggered through the Q-switch of the Nd:YAG laser. A pulse generator (DG 535, Stanford Inc.) was used to synchronize the Nd:YAG laser, the CCD cameras and the injection system.

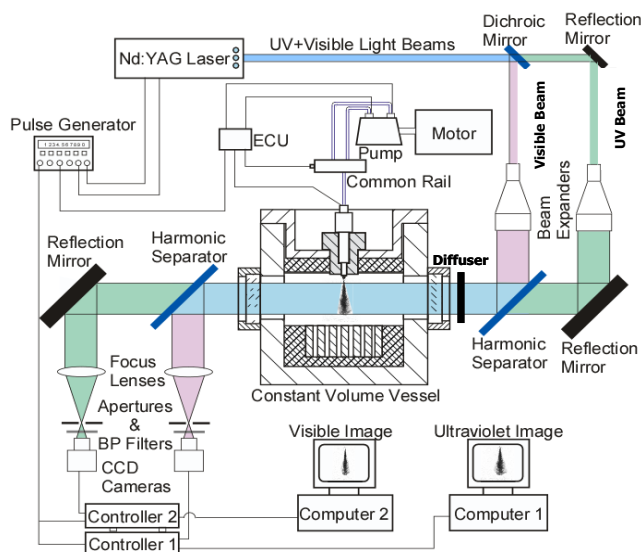


Fig. 7 Experiment setup for the LAS measurement

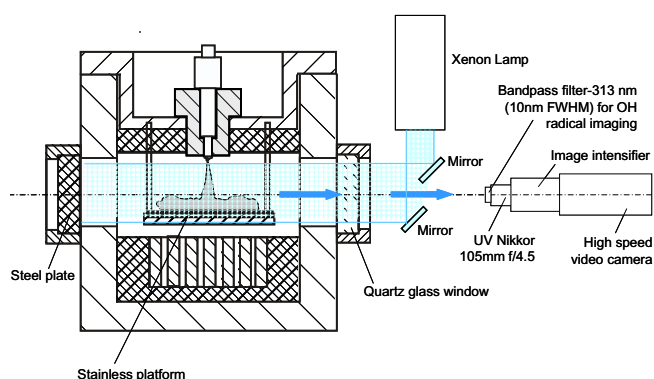


Fig. 8 Setup for the visualization of spray development and combustion inside a high pressure vessel

SETUP FOR VISUALIZATION OF LIQUID SPRAY AND SPRAY COMBUSTION

Figure 8 shows the experimental setup for the visualization of Mie-scattered spray images, direct flame images and OH chemiluminescence images. The experiment was performed inside the high pressure vessel with an ambient pressure of 4MPa and an ambient temperature of 900K. A Xenon lamp was utilized to simultaneously capture the Mie-scattered spray images inside the high pressure vessel and direct flame images. A high speed camera equipped with an UV lens was utilized to record the spray and flame images. An image intensifier was equipped in front of the high speed camera especially for the visualization of OH radical to detect weak OH chemiluminescence. To detect the OH radical without the luminous light, the images of light emission at 310nm was obtained using a bandpass filter installed in front of the lens. The frame speed of the high speed camera was set to 20000fps (frame per second) with an exposure time of 50 μ s.

HIGH PRESSURE INJECTION SYSTEM

A common rail injection system (ECD U2-P, Denso Co.) was employed to supply the stable pressure to the injector. The common rail pressure was set via an engine control unit (ECU) with a pressure control valve (PCV). The maximum pressure of common rail injection system was 170MPa. The injection pulse duration was determined by the preliminarily measured injection rate results.

GEOMETRICAL NOZZLE PARAMETERS AND EXPERIMENTAL CONDITIONS

DEFINITIONS FOR NOZZLE GEOMETRY – The group hole nozzles with various included angles were specially designed and built for this study. It should be noted that, the group-hole nozzle is geometrically non-axisymmetric, that is, there are two view directions. If the incident light comes from a direction vertical to the plane formed by the axes of the two orifices at $\beta=0$ case, the view direction is called “parallel direction” in this study. Similarly, if the direction of incident light is parallel to that plane, it is “vertical direction”. Figure 9 shows the definitions for describing nozzle orifice arrangement. The angle between orifices (included angle: β) can be defined from vertical view direction and interval between orifices (B) can be presented from the parallel view direction. The following experimental results are arranged based on these two view directions.

NOZZLE SPECIFICATIONS – Table 1 shows the nozzle specifications applied for this study. The diameter of each orifice (D) of all test group hole nozzles was 0.096mm and the orifice length (L) was 0.8mm. Two single hole nozzles with diameters of 0.135mm and 0.096mm were also applied for the comparison of mixture formation among group hole nozzles. The β angle variance was from 0° to