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EFFECT OF STRATIFIED STRUCTURE OF WALL IMPINGEMENT DIESEL SPRAY ON IGNITION CHARACTERISTICS
(Stereoscopic image analysis using two-way fiber optical system)

Tomohiro Kawaguchi 1, Tomohiko Furuhashi 2 and Masatake Arai 3

1 Graduate Student, Department of Mechanical System Engineering, Gunma University, m05m417@gs.eng.gunma-u.ac.jp
2 Associate Professor, Department of Mechanical System Engineering, Gunma University, furuhata@me.gunma-u.ac.jp
3 Professor, Department of Mechanical System Engineering, Gunma University, arai@me.gunma-u.ac.jp

ABSTRACT In this study, the effect of stratified structure of wall impingement diesel spray on ignition characteristics were experimentally investigated. Appearance positions of OH and C2 radical luminosities and luminous (yellow) flame kernel were stereoscopically observed using a two-way fiber optical system. The interference filter and the image intensifier were used to detect the light emitted from OH or C2 radical. The luminous flame was observed without them. Normal wall was fixed in a high temperature and high pressure combustion chamber. Effects of injection pressure and ambient temperature on ignition characteristics were investigated. The appearance position of OH luminosity corresponds to the ignition point of spray and luminous flame means combustion with soot formation. Ignition points were distant from the impingement point in radial direction. From those results, it was considered that well mixed air-fuel mixture was formed in the spray periphery. The radial position of ignition was shifted to the larger radial location when the injection pressure increased. On the other hand, the appearance positions of luminous flame kernel were distributed in the narrow central area on the wall. This distribution shows that fuel-rich combustion with soot formation started in that area. The appearance positions of C2 luminosity were found slightly inner side in radial direction compared with those of OH luminosity. In the condition of low ambient temperature, low-temperature oxidation reactions were observed. In this condition, low-temperature flame could be observed using C2 interference filter. The appearance positions of C2 radical luminosity appeared far apart from the impingement point.

Keywords: Diesel Engine, Fuel Injection, Ignition, OH Luminosity, C2 Luminosity, Luminous Flame, Wall Impingement Low-Temperature Oxidation Reaction

1. INTRODUCTION

In a small size direct injection diesel engine, the injected spray is impinged to a wall of combustion chamber and its distribution is strongly affected by the interaction between spray and wall and also affected by injection pressure.

Many researchers have investigated new technologies to reduce the harmful emissions such as PM, NOx and THC from a DI diesel engine. Recently, to enhance the air entrainment of the diesel spray, a common-rail injection system has been used [1]. The optimum control of ignition delay was important matter in a pre-combustion process of diesel spray [2][3]. Then many researchers have investigated the ignition delay [4][9].

It was well known that the local air entrainment in a combustion zone of spray mixture was suppressed by a flame that enveloped the mixture because of thermal declination of turbulent mixing. Then the ignition point was considered as the key combustion process as well as the ignition delay. Furthermore since luminous flame was strongly related to a soot formation zone, appearance position of luminous flame had to be investigated to reduce the PM emission.

Low-temperature ignition is characterized by weak, pale blue light emission [10]. It has been difficult to distinguish the first onset of the low-temperature flame.

In this study, appearance positions of OH and C2 radical luminosities and luminous flame kernel were stereoscopically observed using a two-way fiber optical system. Furthermore first appearance position of the low-temperature flame was observed and the effect of injection pressure on it was investigated.

2. EXPERIMENTAL APPARATUS AND METHOD

Schematic of experimental apparatus is shown in Fig.1. Experimental apparatus mainly consisted of three

![Diagram](image-url)
sub-systems. There were a combustion equipment system, a single shot injection system and a high-speed video system. Combustion equipment consisted of a pressure chamber and an electric heater that was installed in the bottom of the chamber. The chamber had two quartz optical windows for stereoscopic observation of ignition phenomena. The flat impingement wall was installed in the pressure chamber. It was set normal against the center axis of injected spray. Distance from the nozzle tip to the impingement point on the wall was set at 50mm. The size of the chamber was ø120mm x 230mm. High-pressure air (3MPa) was charged to the chamber through the electric heater. The charging air was heated up to a test temperature (553K – 803K). A test temperature in combustion chamber was used as the representative ambient temperature T_e of the experimental condition.

Injection system consisted of a pulse generator, a common-rail controller, a supply pump, a common-rail and an injector. The injection nozzle was a single-hole type with hole diameter of 0.17mm. The injection pressure was changed from 35MPa to 150MPa. In order to keep the constant amount (20mg/st) of fuel injection, the injection period was changed from 2.5ms to 5.0ms. JIS No.2 diesel fuel was used as a test fuel. The injection rate shown in Fig.2 was measured using a Bosch - type (long tube method) injection rate meter. It was found that all injection rates were kept almost constant during the injection periods.

The two-way optical system for stereoscopic observation consisted of a couple of objective lens units, a couple of image fibers and a relay lens unit. Using the two objective lens units, front and side views of ignition phenomena could be observed. The relay lens unit that could capture two images in a single optical plane was mounted in front of the high-speed video camera. The high-speed video system consisted of an interference filter, an image intensifier (sensitive wavelength region: 180nm-840nm), high-speed video camera (380nm-800nm) and a recording system of video image. The camera speed was 4500 frames per second.

The interference filter and the image intensifier were used to detect luminosities of OH \[\text{OH}^{+}\] and C_2 in a flame. Center wavelength of the OH interference filter was 306nm (half width=6nm) and maximum transmittance was 35%. Center wavelength of the C_2 interference filter was 516.5nm (half width=12nm) and maximum transmittance was 80%. The green light from Swan band of C_2 radical was captured by this filter system [14]. Appearance position of luminous flame was also observed. Ordinary lens system without an interference filter and an image intensifier were used for this purpose.

Ignition point and appearance position of luminous flame kernel were defined as the first appearance of OH luminosity and that of luminous flame. The definition of coordinate system and symbols used in an image analysis are shown in Fig.3. The coordinate system expressed with O-xyz was used in the analysis. The origin of this coordinate system was set on the wall at the impingement point. In O-xyz system, axis z conformed to the spray injection axis.

3. RESULTS AND DISCUSSION

3.1 Characteristics of wall impingement spray

In order to define clearly the geometric relationship between ignition point and the spray geometry, spray configuration and its penetration were investigated for the condition of non-evaporated impingement spray. Figure 4 shows the penetration of the spray. In this figure, L_z and L_r indicate the growth distance of longitudinal spray and that of radial spray respectively [13]. The spray penetration
increased rapidly with an increase of injection pressure. The growth rate of $L_+$ was especially affected by the injection pressure. Even if the injection pressure was higher than 90MPa, a liquid sheet was observed near the impingement point. And there was no apparent change of spray structure with an increase of the injection pressure.

3.2 Flammable limit

The effects of injection pressure and ambient temperature on flammable limit were investigated. The result was shown in Fig.5. In this figure, the hollow circular symbol indicates ignition. The cross symbol indicates non-ignition. From this figure, it was found that non-ignition area became wider with increase of injection pressure. It was considered that fuel concentration in spray was too lean for ignition as the injection pressure became high.

In the condition of low-temperature, only blue flame was observed. In this figure, hatching area indicates blue flame area. In other words, it is low-temperature flame.

3.3 Effect of ambient temperature on ignition delay

In the series of author’s experimental studies concerning with ignition delay and delay for luminous flame appearance, effects of ambient temperature, impingement angle and injection pressure were reported [13], [15]. From these results, it was found that both impingement angle and injection pressure were not meaningful difference of ignition delay.

$C_2$ luminosity from Swan band could be observed almost simultaneously with OH luminosity in hydrocarbon flame and $C_2$ intensity is higher than OH. Then $C_2$ luminosity could be captured in a weak flame such as low-temperature flame (CASE 2) [14]. Effect of ambient temperature on delays for appearances of OH luminosity, $C_2$ luminosity and luminous flame was shown in Fig.6. These plots included in various injection pressures. In this figure, the experimental line obtained from the numerous data is indicated for the simplicity of the results. In the condition of temperature range of 703K to 803K (CASE 1), there were no obvious differences among them.

Relations between delay for $C_2$ luminosity appearance and ambient temperature are shown in Fig.7. The injection pressures were $P_{inj} = 35MPa$, 90MPa, 120MPa, 150MPa. There were no apparent differences among injection pressures in CASE 1. In the condition of low-temperature (CASE 2), only slight blue-green flame was observed. It was considered that low-temperature oxidation reaction was appeared. In this condition, it was found that delay for $C_2$ luminosity appearance did not depend on ambient temperature, but it depended on the injection pressure.

3.4 Appearance positions of OH and $C_2$ radical luminosities and luminous flame kernel (CASE 1)

First appearance positions of OH and $C_2$ radical luminosities and luminous flame kernel on O-xyz coordinate system were reconstructed from the images captured by the high-speed video camera. The effects of injection pressure on them are shown in Figs.8-10.

In CASE 1, the results of 35MPa injection are shown in Fig.8. In this figure, all the data corresponding to the ambient temperature range of 703K to 773K were included.
Fig. 8 Relative positions of OH and C2 radical luminosities and luminous flame kernel on a wall
(Ignition positions projected in x-z plane and x-y plane, normal impingement with 35MPa injection)

The wall temperature was in the range of 653K - 773K. In other words, all the ignition delay data of CASE 1 ranging \( \tau_{ig} = 1.1\text{ms} \) to \( \tau_{ig} = 3.1\text{ms} \) were summed up. The hollow circular symbol indicates ignition point (first appearance position of OH luminosity). The double circular symbol indicates first appearance position of C2 luminosity. The solid circular symbol indicates appearance position of luminous flame kernel. Upper part of the figure shows the x-z plane distributions of appearance positions of OH and C2 radical luminosities and luminous flame kernel. Lower part of the figure shows those positions in x-y plane. In order to show the relationship between spray configuration and ignition position or appearance position of luminous flame kernel, the configuration of non-evaporated impingement spray at 2.0ms after injection start is also shown in Fig.8 (upper part).

From the reconstructed image of x-z plane (upper part), it was found that ignition points appeared in the upward periphery of the impingement spray. Further, from the reconstructed image of x-y plane (lower part), it was found that ignition points were distributed widely in all radial directions. From these results, it was concluded that the onset of ignition appeared apart from the impingement wall. It was considered that the ambient air was effectively entrained in the spray periphery, because well mixed air-fuel mixture was locally needed for ignition.

On the other hand, appearance positions of first luminous flame kernel were distributed on the narrow central area on the wall. This area was limited in the space surrounded with solid line in x-y plane. Appearance positions of luminous flame kernel were obviously different from ignition points. They were limited in a vicinity of the

Fig. 9 Relative positions of OH and C2 radical luminosities and luminous flame kernel on a wall
(Ignition positions projected in x-z plane and x-y plane, normal impingement with 90MPa injection)

Fig. 10 Relative positions of OH and C2 radical luminosities and luminous flame kernel on a wall
(Ignition positions projected in x-z plane and x-y plane, normal impingement with 120MPa injection)
impingement wall where an adhering liquid sheet was observed in the non-evaporated impingement spray. It was considered that luminous flame kernel corresponding to an onset of fuel rich flame and also an onset of soot formation might start there.

Further the appearance positions of C<sub>2</sub> luminosity were found slightly inner side in radial direction compared with those of OH luminosity. It is inferred that the position of C<sub>2</sub> luminosity indicated the fuel-rich side of diffusion flame near the ignition point.

From these results, it was considered that wall impingement diesel spray was stratification spray.

The results of 90, 120MPa injection are indicated in Figs.9 and 10. The both ambient and wall temperature ranges of data accumulation were the almost same as Fig.8. The configurations of non-evaporated impingement spray at 2.0ms after injection start are also shown in these figures. Ignition points shown in x-z plane appeared in the periphery of the impingement spray. Ignition points shown in the x-y plane were distributed in a space outside of appearance area of luminous flame.

The appearance positions of C<sub>2</sub> luminosity were mixed with ignition points (appearance positions of OH luminosity) as the injection pressure became high. Therefore it was considered that the mixing of fuel with ambient air was promoted with an increase of injection pressure.

According to the spray penetration shown in Fig.4, the growth distance of radial spray at 2.0ms after the injection start was about L<sub>r</sub> = 45mm. However the radial positions of ignition were limited within the area of r = 35mm. It was inferred that ignition did not appear in the spray tip portion. It seems that fuel concentration in the spray tip portion was too lean for ignition when the injection pressure was high. On the other hand, the appearance positions of luminous flame kernel were limited on the wall surface near the impingement point.

From these results, it was clear that ignition points changed with the injection pressure but appearance positions of luminous flame kernel did not depend on the injection pressure. It was inferred that the ambient air was entrained effectively in the spray periphery in the case of P<sub>inj</sub>=35MPa, but in the case of P<sub>inj</sub>= 90MPa, 120MPa, the ambient air was too much entrained in the spray tip portion. Even if the injection pressure was high, appearance positions of luminous flame kernel were limited on the wall surface near the impingement point. Therefore, it was inferred that fuel rich mixture was formed there.

### 3.4 Appearance positions of C<sub>2</sub> radical luminosity (CASE 2)

In the condition of low ambient temperature (CASE 2), the combustion phenomena could not be captured by the OH interference filter because maximum transmittance was 35%. Then the appearance positions of C<sub>2</sub> radical luminosity were investigated. The result is shown in Fig.11. In this figure, all the data corresponding to the ambient temperature range of 653K to 673K are included. The wall temperature was in the range of 613K- 663K. The ignition delay of low-temperature ignition was in the range of τ<sub>ign</sub> = 3ms to τ<sub>ign</sub> = 7ms. The estimated position of non-evaporated spray tips at t = 4.0ms are also indicated in the upper figure of Fig.11. From this figure, it was found that appearance positions of C<sub>2</sub> radical luminosity appeared apart from the impingement point. As for distance from impingement point to appearance positions of C<sub>2</sub> radical luminosity, distance in CASE 2 was further than CASE 1. There was no meaningful difference of the appearance positions of C<sub>2</sub> radical luminosity among injection pressures. Since the spray injection was already finished at t = 4.0ms, spray might be spread like a doughnut shape ring. According to the estimated position of non-evaporated spray at t = 4.0ms, low-temperature ignition might start in the main body of spray.

### 4. CONCLUSIONS

From the experiment of the effect of stratified structure of wall impingement diesel spray on ignition characteristics, the following conclusions were derived.

1. Non-ignition area became wider with increase of injection pressure. In the condition of low-temperature (600K-680K), only blue flame was observed.
2. Delay for C<sub>2</sub> luminosity appearance became short as
the ambient temperature elevated. In the condition of low-temperature, delay for C2 luminosity appearance did not depend on ambient temperature, but it depended on the injection pressure.

(3) Ignition position detected by OH radical luminosity was distributed widely on the radial spray.

(4) In the case of 35MPa injection, the appearance positions of C2 luminosity were found slightly inner side in radial direction compared with those of OH luminosity. However the appearance positions of C2 luminosity were mixed with ignition points as the injection pressure became high.

(5) The appearance positions of luminous flame kernel were observed on the wall surface near the impingement point. It did not depend on the injection pressure.

(6) In the condition of low-ambient temperature (CASE 2), low-temperature ignition positions detected by C2 radical luminosity appeared far apart from the impingement point.

5. REFERENCES