

Combustion analysis of Hydrogen-DDF mode based on OH* chemiluminescence images

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Abstract

Hydrogen–diesel dual-fuel combustion processes were visualized using an optically accessible rapid compression and expansion machine (RCEM). A hydrogen–air mixture was introduced into the combustion chamber, and a pilot injection of diesel fuel was used as the ignition source. A small amount of diesel fuel was injected as the pilot fuel at injection pressures of 40, 80, and 120 MPa using a common rail injection system. The injection amounts of diesel fuel were varied as 3, 6, and 13 mm³. The amount of hydrogen was manipulated by varying the total excess air ratio (λ_{total}) at 3 and 4. The RCEM was operated at a constant speed of 900 rpm, and the in-cylinder pressure and temperature at the top dead center (TDC) were set as 5 MPa and 700 K, respectively. The combustion processes were visualized via direct photography and hydroxyl (OH*) chemiluminescence photography using a high-speed camera and an image intensifier. The results indicated that the diesel mixture first ignited near the wall of the piston bowl, and the flame spread in the hydrogen–air mixture. It was also found that a reduced λ_{total} shortened the combustion duration, with an increased tendency of the heat release rate to shift from a dual peak to a single peak.

Introduction

Because the combustion of fossil fuels in internal combustion engines is one of the main sources of carbon dioxide emissions, it is essential to reduce CO₂ emissions from internal combustion engines to achieve carbon neutrality [1]. Therefore, global interest in the use of carbon-neutral fuels in internal combustion engines is increasing [2–8]. Hydrogen is an interesting candidate for a carbon-neutral fuel. It has the advantages of low ignition energy, which allows wide flammability limits, high flame velocity, and carbon-free combustion [9]. Hydrogen is a renewable fuel derived from a variety of natural and renewable resources [10].

The use of hydrogen in spark ignition (SI) engines has been studied by several researchers [11–15]. However, for compression ignition (CI) engines, the ignition temperature of hydrogen is quite high compared to that of diesel [10]; therefore, hydrogen is not suitable as the sole fuel in CI engines because of its limited ignition ability [10, 16]. The dual-fuel combustion mode, which can ignite high-ignition-temperature gaseous fuels such as hydrogen and natural gas (NG), has attracted considerable interest. They are also reported to have a high probability of achieving higher fuel efficiency and less pollutant emissions than conventional diesel engines [17]. Liquid fuels are used as ignition sources for gaseous fuels to exploit the combustion advantages of gaseous fuels in CI engines. Numerous investigations have been

performed on the dual-fuel mode in CI engines, including the use of hydrogen as one of the fuels. Szwaja and Rogalinski [18] studied the combustion of hydrogen under homogeneous charge compression ignition (HCCI) conditions and hydrogen–diesel dual fuel conditions in a CI engine. They concluded that a compression ratio of at least 16 was required to ignite the hydrogen mixture in the HCCI mode. They also found that the addition of hydrogen as an extra fuel, i.e., using the dual-fuel mode, improves the engine performance owing to high-speed hydrogen flame propagation, which increases the degree of constant volume. Zhou et al. [19] studied the effects of hydrogen addition on the combustion and performance of diesel engines. The hydrogen concentration was manipulated by supplying 10%–40% of the total fuel energy. Improvements in engine performance and emissions of CO and particulate matter (PM) can be achieved for medium to high loads by adding hydrogen. Hydrogen addition also resulted in the reduction of the majority of the unregulated emissions. Several researchers have conducted optical studies on dual-fuel modes. Kim et al. [17] studied the combustion phenomena and emissions of a natural-gas–diesel dual-fuel mode using an optical engine. The NG substitution ratio (NGSR) to the total fuel energy was manipulated by changing the fraction of injected diesel fuel. The results indicated that a higher NGSR reduced the non-premixed flame. However, the replacement of a large fraction of diesel with a low-reactivity fuel, i.e., NG, deteriorates the combustion efficiency and combustion instability. Another optical study on natural-gas–diesel dual-fuel mode combustion was conducted by Lee et al. with the addition of hydrogen [20]. The compressed NG (CNG) substitution ratio was fixed at 70%, and the hydrogen substitution was manipulated at 0 and 30%. They found that hydrogen addition to CNG improved the flame propagation speed, with a higher flame-area growth rate and larger flame-distribution area. Interestingly, it was also discovered that the hydrogen addition mainly affected the initial and middle stages of combustion, while little effect was reported on the late-stage combustion.

As described above, there have been numerous experimental studies on diesel–hydrogen dual fuel CI engines and optical research on diesel–CNG dual fuel. However, knowledge of hydrogen flame formation and propagation in diesel engines is still limited. Recently, Rajasegar et al. [21] investigated the impact of hydrogen addition on the ignition and combustion behavior of a pilot diesel spray in the context of dual-fuel combustion for lean premixed hydrogen internal combustion engines. Through experiments comprising the use of a heavy-duty, single-cylinder, optical engine and zero-dimensional chemical-kinetics simulations, the researchers studied the spatial and temporal evolution of the two-stage autoignition of n-heptane injected into a premixed charge of hydrogen and air. The study also involved the use of high-speed cool-flame and OH* chemiluminescence imaging techniques to understand the ignition behavior and presented

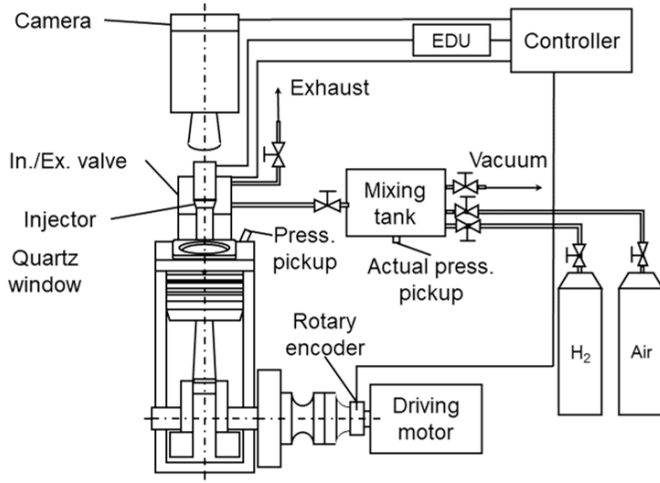


Figure 1. Schematic of the experimental setup.

Table 1. Technical specifications of the RCEM.

Bore × Stroke	102 × 105 mm
Displacement	857 cc
Compression ratio	15.4
Diesel injection system	Common rail injection system
Diesel injector nozzle	0.123 mm × 7

a comparative analysis with NG dual-fuel combustion [21]. The impact of hydrogen and NG concentrations has been the main focus, and the findings revealed that at low concentrations, hydrogen has a stronger inhibitive effect on the pilot-fuel autoignition characteristics than NG, thus resulting in longer ignition delays. Furthermore, at high concentrations, the inhibitive effect of hydrogen tended to become saturated, resulting in a plateau in the ignition delay values with high cyclic variability compared to the case of NG. The flame visualization results indicated that the presence of hydrogen severely hampered the transition between the first- and second-stage auto-ignition reactions, thus resulting in reduced ignition kernels [21]. Other parameters that could influence the ignition and combustion behavior of diesel–hydrogen dual fuels are the characteristics of the pilot injection. Therefore, in this study, the combustion processes of the hydrogen–diesel dual fuel mode were clarified, and the pilot injection characteristics, i.e., injection pressure and quantity were studied in addition to the hydrogen concentration. Therefore, an optically accessible rapid compression and expansion machine (RCEM) that can

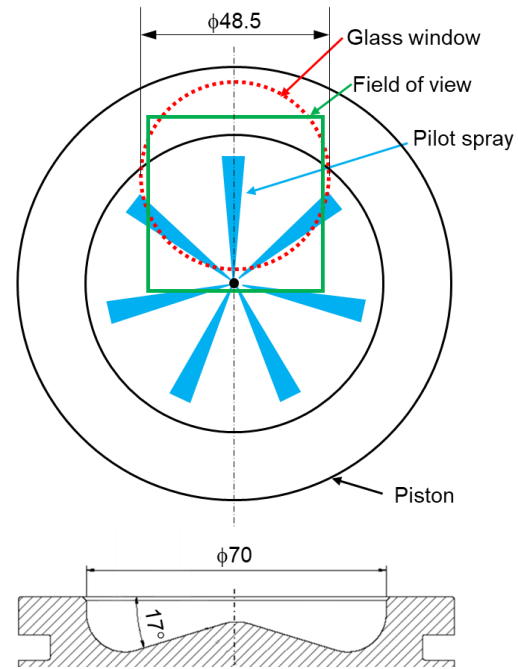


Figure 2. Piston shape and visualization area.

Table 2. Standard experimental conditions.

Cranking speed [rpm]	900
Pressure at TDC [MPa]	5.0 ± 0.1
Temperature at TDC [K]	700
Ignition timing [°ATDC]	2.0±1

simulate a single compression and expansion stroke was employed. OH* chemiluminescence imaging was used to visualize the combustion behavior. Diesel fuel was used for the pilot injection. The total excess air ratio, pilot injection pressure, and pilot injection quantity were varied to clarify the effects of the pilot and intake conditions on combustion.

Experimental Setup

Figure 1 presents a schematic of the experimental setup. In this study, the combustion in a cylinder was visualized using an RCEM modified from a naturally aspirated four-stroke-cycle single-cylinder diesel engine (Yanmar NFD170). The cylinder head of the RCEM was

Table 3. Details of experimental parameters.

Total air excess ratio [-]	3.0					4.0				
Pilot injection pressure [MPa]	40	80			120	40	80			120
Pilot injection quantity [mm ³]	6	3	6	13	6	6	3	6	13	6
Hydrogen energy fraction [%]	85.9	93.0	85.9	69.2	85.9	81.7	90.9	81.7	59.5	81.7
Air excess ratio of intake mixture [-]	3.6	3.3	3.6	4.6	3.6	5.1	4.5	5.1	7.3	5.1
Oxygen concentration of intake gas [vol%]	18.8	18.6	18.8	19.2	18.8	19.4	19.2	19.4	19.9	19.4

designed and manufactured independently such that the quartz window and intake/exhaust valve could be attached to it. A driving motor (Mitsubishi Electric SF-PR18.5KW 4P 200V) connected to the flywheel was driven externally, and the crank angle and TDC position were detected using a rotary encoder (MTL MEH-130-1024P) attached to the shaft coupling. By controlling the opening and closing timings of the intake valve and the timing of the fuel injection signal using a timing controller (LabSmith LC880), it was possible to produce a single compression and expansion stroke for a diesel engine. A general-purpose inverter (Mitsubishi Electric, FR-A820-18.5K-E1) was used to adjust the engine speed while monitoring the crank angle detected by a rotary encoder. A mixture of air and hydrogen was introduced into the combustion chamber through an intake valve connected to a mixing tank. An absolute pressure transducer (KYOWA Electronic Instruments PABA-500KP) and a dynamic strain measuring instrument (KYOWA Electronic Instruments DPM-711B) were used to measure the pressure in the mixing tank. Diesel fuel was supplied using a common-rail injection system. A commercially available diesel fuel (JIS No. 2; density at 15°C: 830.7 kg/m³; lower heating value: 42.9 MJ/kg; cetane number: 55.0) and hydrogen (lower heating value: 120 MJ/kg) are used as fuels.

The RCEM is a modified diesel engine in which the original intake–exhaust valve and fuel injection systems have been removed. The introduction of intake air/hydrogen was facilitated through an independent intake/exhaust valve and a mixing tank, while fuel injection was achieved via a common rail system, thus ensuring experimentally flexible conditions. When operating the RCEM, these systems were controlled via a timing controller that synchronized with the rotary encoder. The RCEM underwent motor-driven operation at 900 rpm for a specific duration, maintaining an open intake and exhaust valve (with no compression or expansion stroke during this time). As the intake temperature reached the prescribed temperature, a singular trigger signal was sent from the timing controller, which prompted the closure of the intake valve and the injection of fuel at a predetermined crank angle position, thus facilitating the production of a complete compression and expansion stroke in a diesel engine without residual gas effects. The specifications of the test RCEM are summarized in Table 1.

Two photography methods are proposed in this study: direct imaging and OH* chemiluminescence imaging. For direct imaging, a continuous green solid-state laser (Civil Laser LSR532N-5 W) having a wavelength of 532 nm was irradiated at an output of 5 W to capture the Mie-scattered light from the diesel spray. A high-speed color camera (Photron Fastcam SA-Z) was used to capture the spray behavior visually. For the OH* chemiluminescence imaging, the chemiluminescence wavelength was 309 nm; hence, an ultraviolet transmission lens (Nikon UV-Nikkor; center wavelength 105 mm; F value 4.5) was used. Because the OH* chemiluminescence intensity was very low, an image intensifier (HAMAMATSU C10880-03F) and a bandpass filter (ASAHI SPECTRA UZ0310, center wavelength 310 nm, half width 10 nm) were attached to the high-speed camera. The imaging conditions for both photography methods are listed in Table 4. The visualization area for both techniques was the range in which the three pilot spray plumes could be captured, as shown in Figure 2.

To study the combustion behavior of the diesel–hydrogen dual fuel mode, the total excess air ratio, pilot injection pressure, and pilot injection quantity were manipulated. The standard experimental conditions are listed in Table 2. The cranking speed was 900 rpm, and the in-cylinder pressure and temperature were 5 MPa and 700 K, respectively. The pilot injection timing was adjusted to fix the ignition timing at 2°ATDC for all the conditions. The detailed experimental parameters are listed in Table 3. For the pilot injection conditions, the

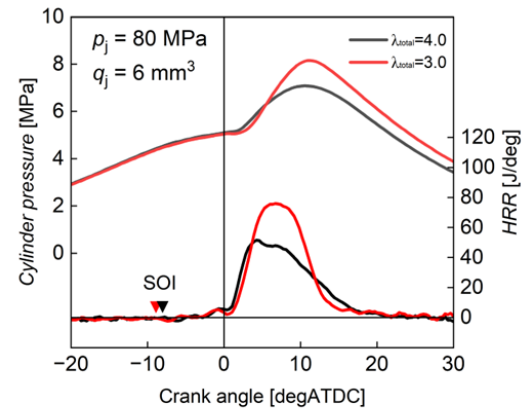


Figure 3. Effects of λ_{total} on in-cylinder pressure and heat release rate with the standard pilot injection.

Table 4: Imaging conditions for the photography methods.

	Direct imaging	OH* chemiluminescence
Flame rate [fps]	50400	50400
Range [pixel×pixel]	512×512	512×512
Resolution[mm/pixel]	0.0933	0.0951
Exposure time [ms]	0.16	18.23
I.I. gain	-	900
I.I. gate	-	continuous

injection pressure $p_i = 80$ MPa and injection quantity $q_i = 6$ mm³ were referred to as standard conditions. First, the effect of the hydrogen fraction was studied by manipulating the total excess air ratio λ_{total} at 3 and 4 with the standard pilot injection. Next, the effect of the pilot injection pressure was investigated. The injection pressure was varied as 40 MPa, 80 MPa, and 120 MPa with the standard injection quantity for each total air excess ratio. Finally, the influence of the amount of pilot injection was observed by controlling the diesel injection quantity at 3, 6, and 13 mm³ using the standard pilot injection pressure at each total excess air ratio. When the total excess air ratio was fixed, that of the hydrogen mixture increased with the pilot injection quantity. Three experiments were conducted under each condition. All the results presented below are the selected representative single-cycle data, which are the closest results to the average of the three experiments under each condition.

Results and Discussions

Effects of H_2 Concentration

First, OH^* imaging was performed for $\lambda_{total} = 3$ and 4 with the standard pilot injection. Figure 3 presents the in-cylinder pressure and heat release rate (HRR). The start of injection (SOI) was adjusted such that the ignition timing occurred at 2°ATDC for all the conditions. In this study, the ignition timing is defined as the crank angle at which the HRR was approximately 5 J/deg . The duration of injection (DOI) for this work is approximately $2\text{--}3^\circ\text{CA}$, depending on the injection conditions. Ignition occurred after the end of the injection for all the conditions. As observed, the pilot injection started earlier for $\lambda_{total} = 3$. This is owing to the lower oxygen concentration in the premixture for a lower λ_{total} and the chemical inhibition effect of hydrogen, which causes an elongated ignition delay of the pilot spray [21]. In this study, the ignition delay is defined as the time from the SOI to the ignition timing. The HRR peak—either a single peak or dual peak—indicates significant information in the DDF study. The dual-peak HRR indicates that combustion of the air–hydrogen mixture occurred after that of the diesel and hydrogen mixture [19]. This behavior was observed at an HRR of $\lambda_{total} = 4$. As λ_{total} decreased to 3 with the addition of more hydrogen, the HRR shifted toward a single peak with a higher maximum heat release and shorter combustion duration. At $\lambda_{total} = 3$ and 4, the excess air ratios for the hydrogen fuel alone were 3.6 and 5.1, respectively. Therefore, the richer hydrogen was ascribed to a shorter combustion duration, in which the high flame propagation speed of hydrogen increased the HRR [20].

Figure 4 presents the combustion process with a standard pilot injection for $\lambda_{total} = 3$ and 4. As for the results of direct photography, only the diesel spray could be visualized because the flame was almost non-luminous. The results are described in the final section. The visualized OH^* images are presented here. Under the condition of λ_{total}

$= 4$, a bright region rapidly appears near the edge of the piston bowl after the ignition begins and then spreads alongside the wall of the piston bowl until approximately 3.5°ATDC , which is followed by the expansion of the low-brightness area from these regions. It should be noted that it was impossible to distinguish between the combustion regions of diesel fuel and hydrogen in this work. However, when estimating the distribution of diesel fuel owing to spray, it can be assumed that the high-brightness area extending up to approximately 3.5°ATDC is a region with a high local equivalence ratio wherein the diesel fuel mainly burns, and there is a high possibility that the low-brightness area that spreads beyond that region is a high-temperature area owing to the hydrogen premixed combustion. Compared to the condition of $\lambda_{total} = 3$, the intensity of OH^* is weaker at $\lambda_{total} = 4$ and hardly spreads beyond 11.5°ATDC . As can be observed from the HRR behavior in Figure 3, the heat release continued even at subsequent crank angles, suggesting that the flame temperature at that time was low; hence, the OH^* chemiluminescence intensity was low. Meanwhile, at $\lambda_{total} = 3$, the combustion regions of the diesel fuel and hydrogen appear almost simultaneously, corresponding to the single-stage HRR in Figure 3. In addition, a region with a high OH^* intensity can be observed even at the latter stage of combustion, which suggests that the flame temperature is higher.

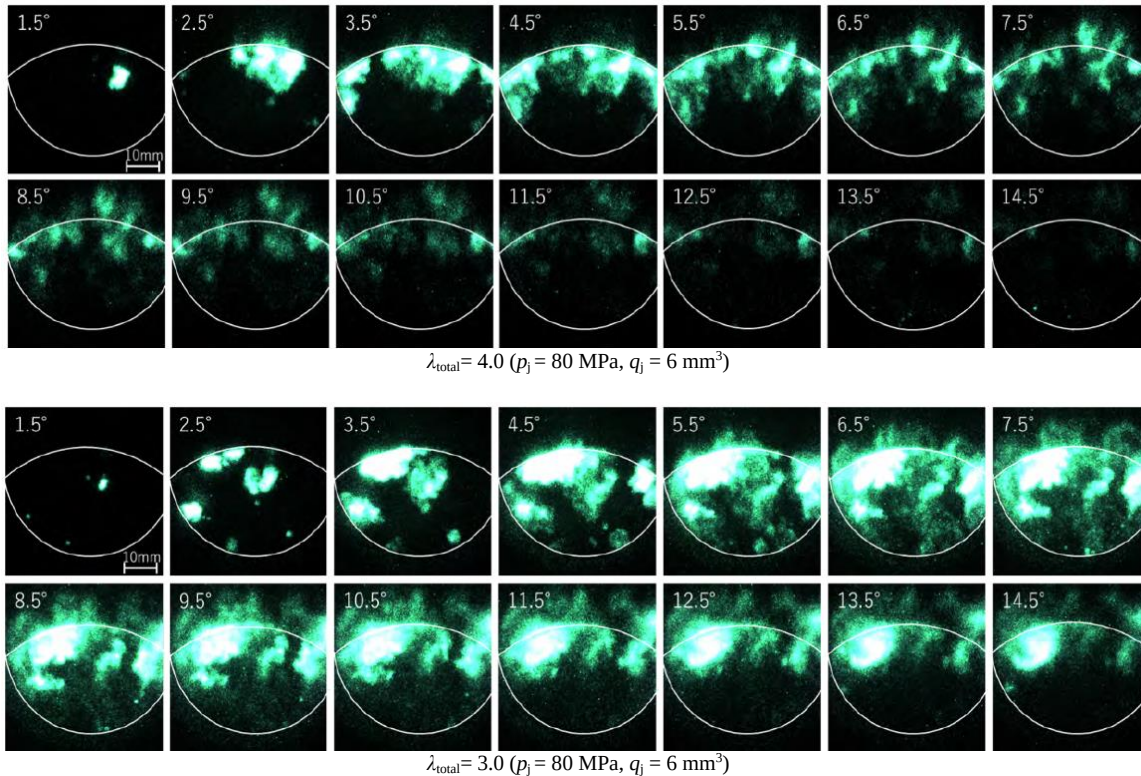


Figure 4. Visualized images using OH^* photography with respect to λ_{total} .

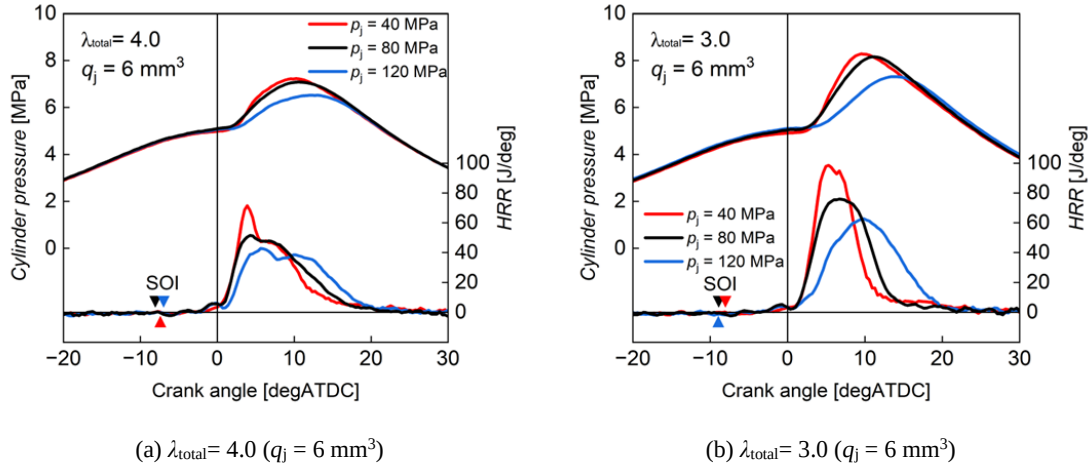


Figure 5. Effects of pilot injection pressure on in-cylinder pressure and heat release rate with the standard pilot injection for (a) $\lambda_{total} = 4.0$ and (b) $\lambda_{total} = 3.0$.

Effects of Pilot Injection Pressure

The effect of varying the pilot injection pressure was investigated. Figure 5 presents the in-cylinder pressure and HRR at the injection pressures of 40, 80, and 120 MPa for both λ_{total} . The injection pressure hardly exhibits any effect on the ignition delay, which agrees with the findings of Lyn regarding the effect of the injection pressure on the ignition delay [23]. As the injection pressure decreased, the diesel mixing rate decreased and the local equivalence ratio increased considerably, which provides favorable conditions for the ignition of the pilot spray. This resulted in a rapid increase and a higher peak for initial combustion. As the injection pressure increased, the dual-peak HRR became more significant at $\lambda_{total} = 4$.

Figure 6 presents the OH* images with varying injection pressures under the conditions of $\lambda_{total} = 3.0$ and $q_j = 6 \text{ mm}^3$. When the injection pressure was 40 MPa, the bright region rapidly spread from upstream of the diesel spray in the direction of the spray immediately after ignition. Subsequently, the diesel spray shape was maintained for a long time until 9.5°ATDC . Under low-injection-pressure conditions, the momentum of the spray was small, and the mixing rate was low. Consequently, ignition occurred in the middle of the spray development, and a flame was formed corresponding to the diesel–air mixture distribution. When the injection pressure was increased to 120 MPa, ignition occurred near the edge of the piston bowl, from where the low-luminosity region spread to the entire visualization range by 9.5°ATDC . Compared with the low-luminosity-region expansion at 80 MPa in Figure 4, the low-luminosity region expansion at 120 MPa was slower, and the expansion continues until 9.5°ATDC . Owing to the increased spray-tip penetration and momentum, ignition occurred at the edge of the piston bowl. This was followed by the expansion of the ignition region with low luminosity until 9.5°ATDC , which is thought to be the expansion of the diesel–hydrogen premixed combustion. This is because when the injection pressure is higher, the injection duration is shorter, and ignition occurs after a certain time has passed since the end of injection. This resulted in an increased homogeneity of the diesel mixture in the combustion chamber, which resulted in a slow expansion of the region with low luminosity. This corresponds to a single low HRR peak and a long combustion period at $p_j = 120 \text{ MPa}$, as observed in Figure 4(b).

Effects of Pilot Injection Quantity

The effect of the pilot injection quantity was examined. The HRR under each condition is compared with the injection amount in Figure 7. It can be observed from the conditions of $\lambda_{total} = 3.0$, that the shape of the HRR changes significantly depending on the injection quantity. Compared to the condition of $q_j = 6 \text{ mm}^3$, when the injection quantity was increased to 13 mm^3 , the HRR increased sharply, the peak was high, and the combustion duration was shortened. However, when the injection quantity was reduced to 3 mm^3 , the HRR of the initial stage, which was mainly caused by the combustion of diesel fuel, could not be observed, and the HRR decreased with a longer combustion duration. This is because, as the quantity of pilot injection decreased, the ignition delay increased, the mixing period of air and diesel fuel in the cylinder increased, and slower combustion occurred. A similar tendency was observed under the conditions of $\lambda_{total} = 4.0$ and $p_j = 80 \text{ MPa}$.

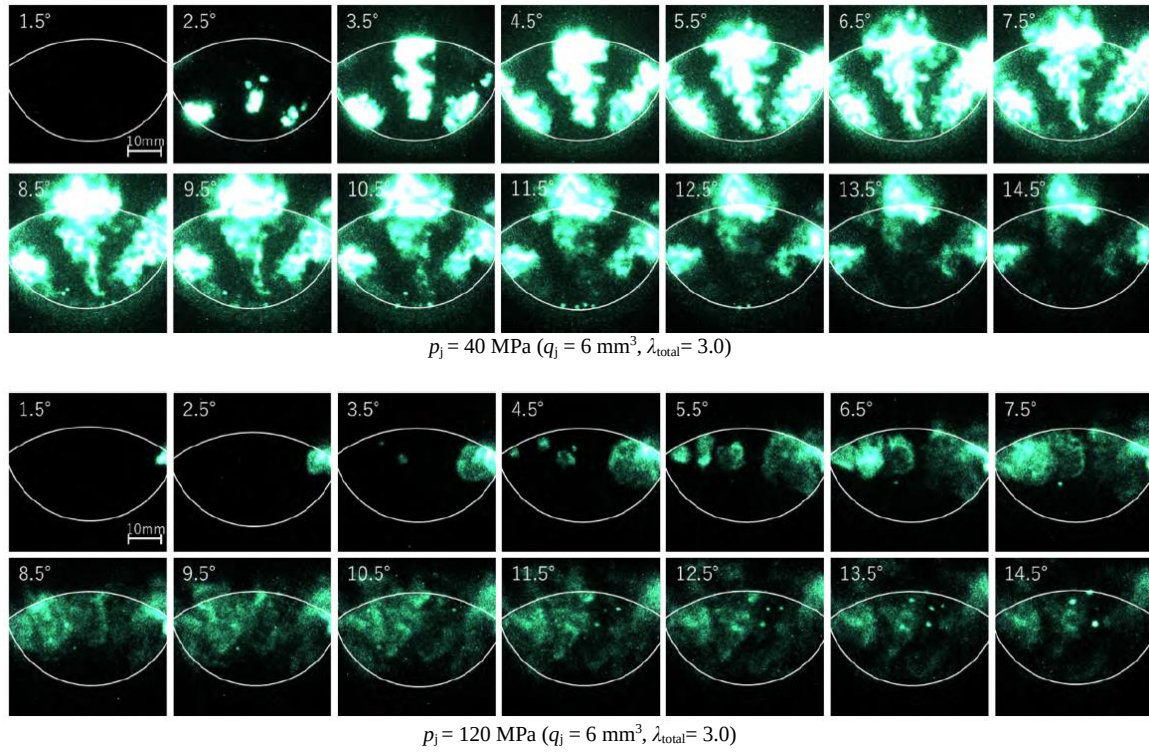
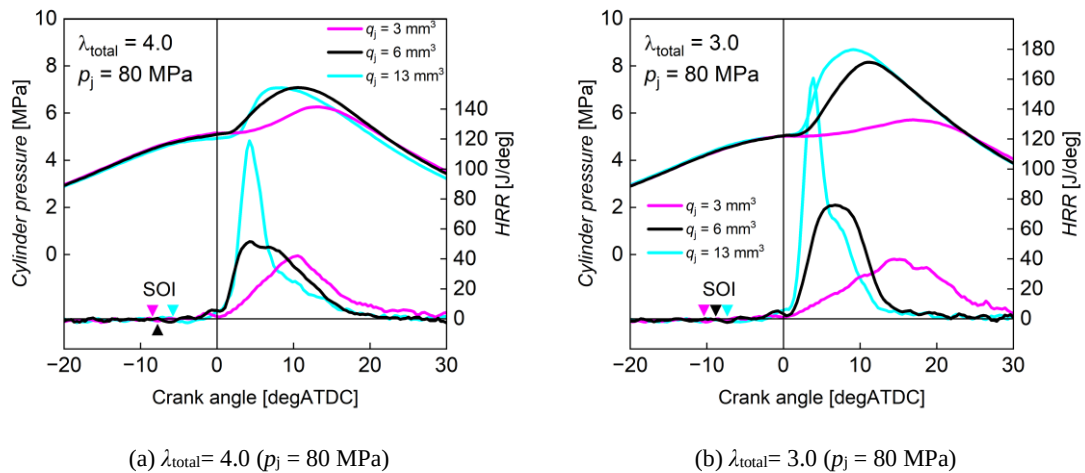


Figure 6. Visualized images using OH* photography with respect to pilot injection pressure.

Figure 8 presents OH* images under the condition of $\lambda_{total} = 3.0$. When the injection amount was increased to 13 mm³, the bright region rapidly spread from approximately 3.5°ATDC along the edge of the piston bowl. The expansion of the high-brightness region corresponds to the rapid increase in the HRR in Figure 7, and it is considered that this combustion mainly consists of diesel fuel. In addition, under these conditions, the burnt gas with momentum spreads to the squish region owing to its long injection duration.

When the injection quantity was decreased to 3 mm³, a high-temperature region appeared at the lower left, which probably originated from the left spray at 1.5°ATDC, and the region with low brightness propagated slowly outwards to the edge of the piston bowl until approximately 13.5°ATDC. Under this condition, with a hydrogen mixture and a low excess air ratio, the propagation of the

region with low brightness is thought to be mainly composed of hydrogen; hence, the temperature is low. At 12.5°ATDC, another bright region appeared at the edge of the piston and slowly spread outwards. It is believed that the unburned hydrogen mixture at the end of the piston bowl was ignited owing to the high temperature and pressure during the expansion of the combustion gas. From these results, it can be inferred that the reduced injection pilot quantity and increased hydrogen fraction under a constant total excess air ratio resulted in slow combustion and a low combustion temperature.



(a) $\lambda_{total} = 4.0$ ($p_j = 80$ MPa)

(b) $\lambda_{total} = 3.0$ ($p_j = 80$ MPa)

Figure 7. Effects of pilot injection quantity on in-cylinder pressure and heat release rate

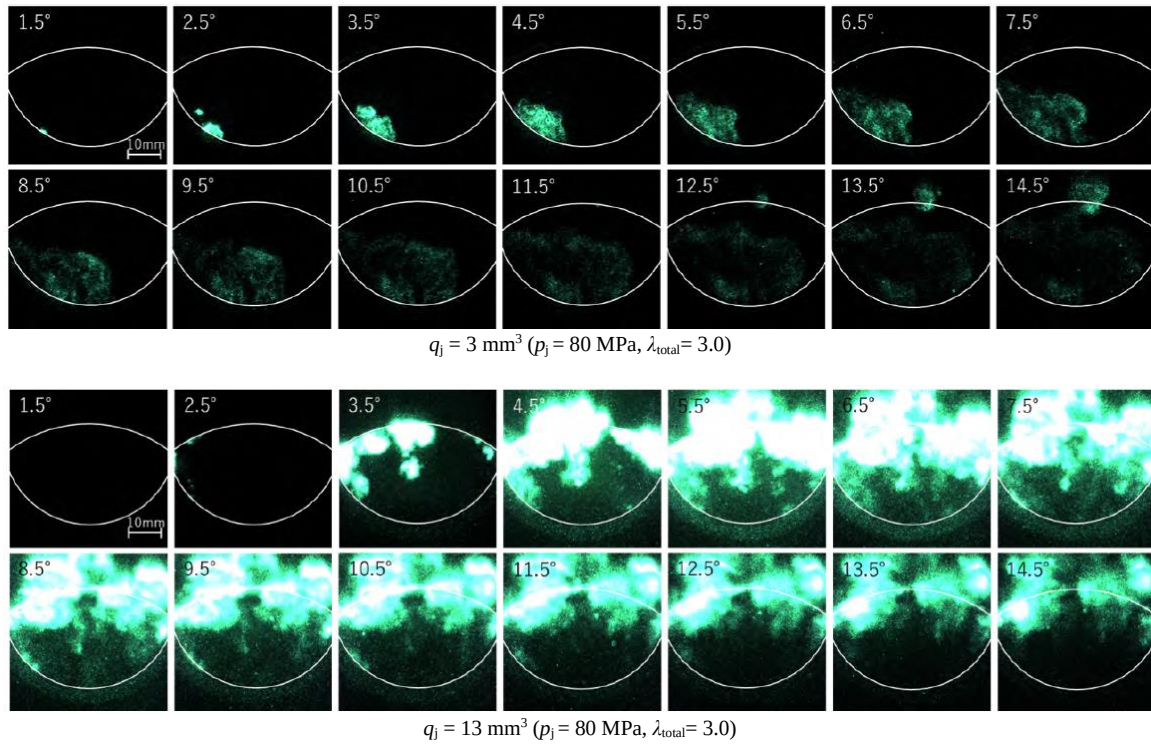


Figure 8. Visualized images using OH* photography with respect to pilot injection quantity.

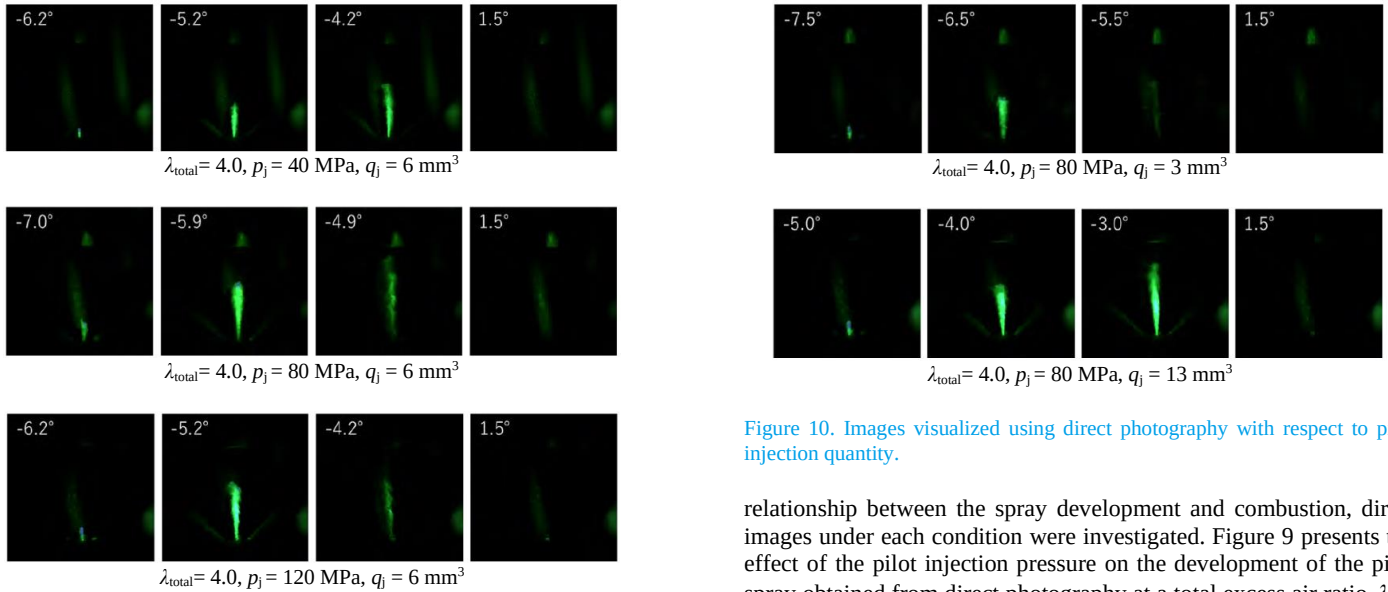


Figure 9. Images visualized using direct photography with respect to pilot injection pressure.

Visualization of Combustion Process using Direct Photography

As mentioned previously, under the present combustion conditions, it is impossible to capture the flame using direct imaging. It is thought that under the present conditions, the ignition delay is very long, thus providing sufficient mixing time for the pilot fuel with air and making the flame more premixed and non-luminous. However, the development process of the pilot spray was captured because the laser irradiated the region where the pilot fuel was injected. To clarify the

Figure 10. Images visualized using direct photography with respect to pilot injection quantity.

relationship between the spray development and combustion, direct images under each condition were investigated. Figure 9 presents the effect of the pilot injection pressure on the development of the pilot spray obtained from direct photography at a total excess air ratio $\lambda_{total} = 4.0$. The bright green region visible before -4° ATDC was the dense region of the pilot spray. The spray tip penetration increased with the injection pressure, and the injection duration decreased. The ignition timing was set at 2° ATDC under all conditions, thus indicating that ignition occurred after the end of the injection. No luminous flames were observed after the ignition.

Figure 10 presents the images obtained using direct photography with varying pilot-injection quantities. The spray development process was similar in the early stage of injection; however, the spray tip penetration was greater for $q_j = 13 \text{ mm}^3$, corresponding to a longer injection duration. However, the DOI was approximately 2.0 to

3.0°C/A; hence, the injection ended before ignition occurred under both conditions.

Conclusions

To clarify the combustion process in the hydrogen–diesel dual-fuel mode, OH* imaging and direct imaging were performed using the RCEM. The total excess air ratio, pilot injection pressure, and pilot injection quantity were varied. The following conclusions could be drawn from this study.

- (1) The high-temperature region caused by the combustion first appeared at the periphery of the piston bowl and spread along its wall. The ignition delay was relatively long, and no luminous flames were observed in the direct imaging. Therefore, the combustion zones of the diesel and hydrogen could not be distinguished. However, based on the estimated distribution of the diesel fuel, it is assumed that the high-temperature region from the late combustion stage spread mainly owing to premixed hydrogen combustion.
- (2) A decreased total excess air ratio with a constant pilot injection reduced the combustion duration, and the HRR tended to shift from a dual peak to a single peak.
- (3) When the injection pressure was decreased, the high-temperature region expanded conically immediately after ignition. However, when the injection pressure was high, the high-temperature region spread along the bowl wall, and the intensity of OH* was relatively weak because ignition occurred well after the end of the injection.
- (4) When the pilot injection quantity was small, ignition occurred near the injection nozzle, and the high-temperature region gradually spread inside the piston bowl. Moreover, the OH* intensity of the premixed hydrogen flame was low owing to the low temperature. Furthermore, as the pilot injection quantity increased, the injection duration increased, and the burned gas with momentum spread to the squish area.

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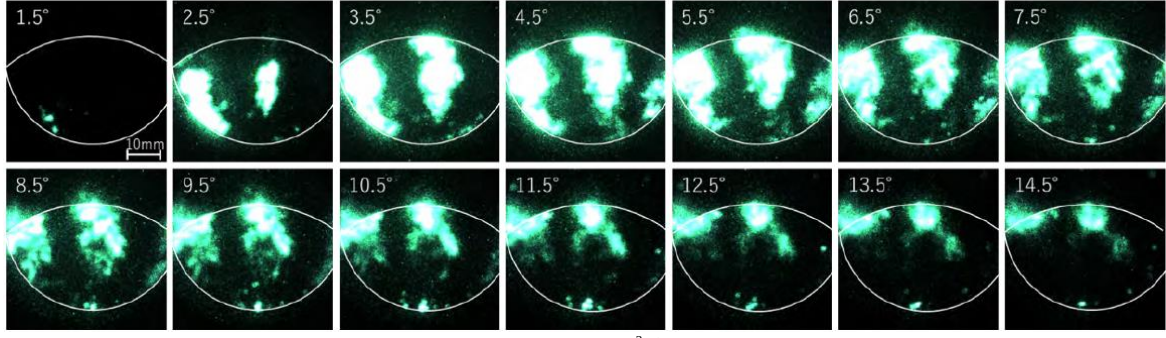
Website of lab.: <http://cpel.energy.kyoto-u.ac.jp/>

Acknowledgments

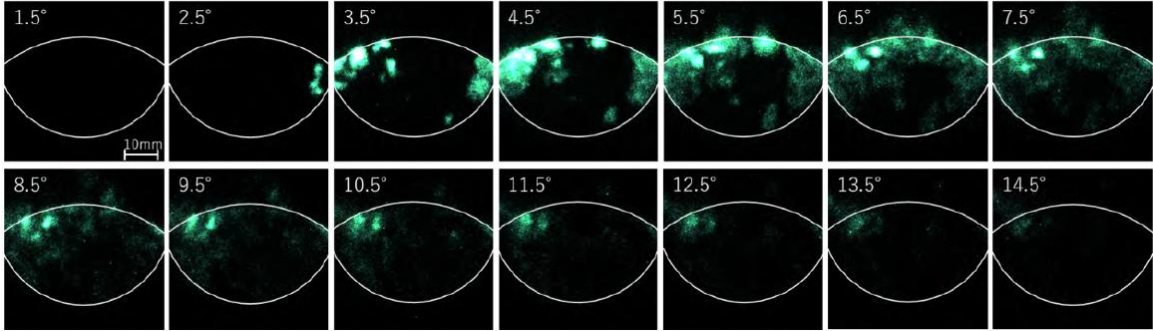
This work was financially supported by Nippon Foundation.

Appendix

Figure A1 shows the OH* images varying injection pressure under the conditions of $\lambda_{\text{total}} = 4.0$ and $q_j = 6 \text{ mm}^3$. Figure A2 shows the OH* images varying injection pressure under the conditions of $\lambda_{\text{total}} = 4.0$ and $p_j = 80 \text{ MPa}$.

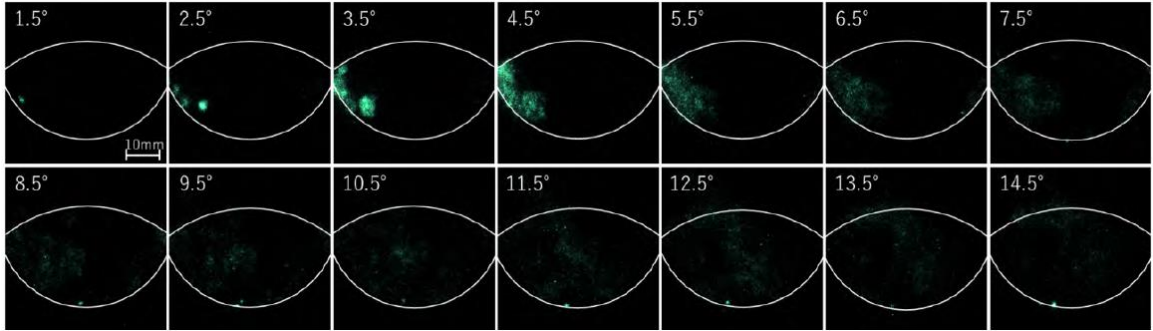


$p_j = 40 \text{ MPa}$ ($q_j = 6 \text{ mm}^3$, $\lambda_{\text{total}} = 4.0$)

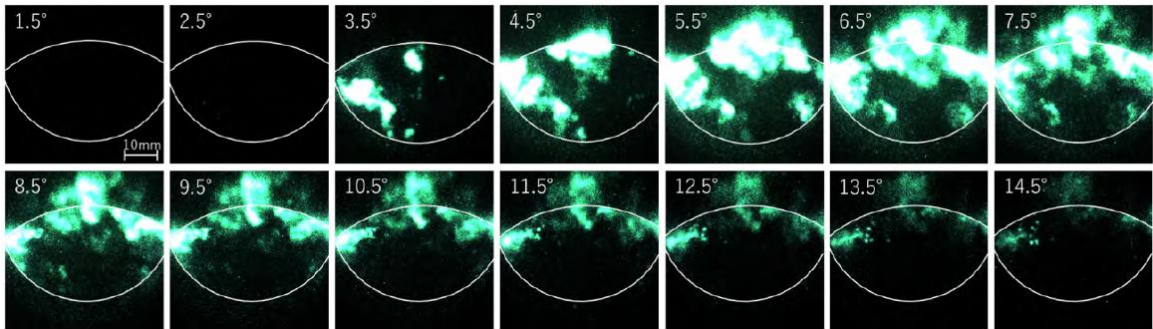


$p_j = 120 \text{ MPa}$ ($q_j = 6 \text{ mm}^3$, $\lambda_{\text{total}} = 4.0$)

Figure A1 Visualized images using OH* photography with respect to pilot injection pressure at $\lambda_{\text{total}} = 4.0$.



$q_j = 3 \text{ mm}^3$ ($p_j = 80 \text{ MPa}$, $\lambda_{\text{total}} = 4.0$)



$q_j = 13 \text{ mm}^3$ ($p_j = 80 \text{ MPa}$, $\lambda_{\text{total}} = 4.0$)

Figure A2 Visualized images using OH* photography with respect to pilot injection quantity at $\lambda_{\text{total}} = 4.0$.