Application of Microwave Enhanced Plasma to Control the Ignition Delay of Diesel Spray Combustion

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Received on November 28, 2016

ABSTRACT: The effect of microwave enhanced plasma (MW Plasma) on ignition delay of diesel spray combustion was investigated inside a constant volume high pressure chamber. A microwave-enhanced plasma system, in which plasma discharge generated by a spark plug was amplified using microwave pulses, was used to introduce plasma to the injected spray before the occurrence of auto-ignition. High speed imaging of natural luminosity indicated an earlier appearance of flame in the with-plasma cases compared to the respective without-plasma conventional operation. These results corresponds well to the behavior of the heat-release rates, suggesting a reduction-effect by MW plasma on the ignition delay of diesel combustion.

KEY WORDS: heat engine, microwave enhanced plasma, diesel combustion, ignition delay, pilot injection, low temperature oxidation [A1]

1. Introduction

Multi injection strategy for the diesel injection was shown to effectively overcome the NOx and soot trade-off of the conventional diesel engines. Pilot injection in these operating conditions is proven to reduce the engine noise levels, and NOx emissions by controlling premixing heat release rates (1). Pilot injection promotes the low temperature oxidation which effectively reduces the ignition delay of the subsequent main injection (2). Recently, Plasma assisted ignition is gaining its prominence due to its ability to control the ignition delay (3), flame stabilization at high speeds (4), and ignition enhancement (5). Ju et al. (6) identified three major pathways by which plasma affects the combustion: thermal, kinetic, and transport. The radical pool generated through the plasma discharge helps in enhancing the reaction rates and altering the reaction pathways that lead to auto-ignition and thermal processes. Out of the radical pool generated by plasma, OH radicals are proven to play a key role in both ignition chemistry as well as combustion chemistry (6). Numerical results indicated that OH radicals are much effective for reaction acceleration at low temperature regimes compared to high temperature thermal ignition regimes (7). The plasma generated OH radicals initiate the hydrogen abstraction reactions, before the traditional path of chain branching reactions to take place for creation of radicals (8). The ability of the microwave (MW) plasma to produce OH radicals (2) is quite attractive for controlling the ignition delay in hydrocarbon fuels.

In the present work, it is proposed to use plasma generated radicals to control the ignition delay of diesel spray combustion. Ikeda et al. (3) developed the microwave enhanced plasma system that proven to enhance the initial flame kernel and can generate the large amount of OH radicals even at 2MPa pressure (9). This system was used in present work to generate the plasma, and the effect of duration of plasma-spray interaction, and time delay between start of injection and plasma radiation were studied. Ignition delay was computed from the in-cylinder pressure histories for all the conditions tested. The results were compared with the double injection case (with main injection and pre-injection), which is known to decrease the ignition delay due to the promotion of low temperature oxidation. In addition to pressure measurements, the high speed imaging was carried out to visualize the combustion event from all tested cases and a qualitative comparison was made between the tested conditions.

2. Experimental Setup

The experiments were conducted in an optically accessible pre-burn type constant volume combustion chamber. The combustion chamber was in cylindrical shape with total volume of 200 cm³, with 60 mm diameter optical windows. The schematic layout of the experimental setup is shown in Fig. 1. In pre-burn type combustion chamber, the ambient pressure and ambient gas composition that are required for diesel auto-ignition were created by igniting a premixed combustible gas mixture. Initially, known quantities of propane, oxygen and nitrogen gases were filled to a separate premixing chamber, where all three gases were mixed for long enough time for good mixing. Following the mixing, combustible mixture was sent to combustion chamber to the required pressure (0.6MPa in all experiments presented in this paper). The chamber pressure was monitored using a pressure sensor (Kistler 6052C) mounted on
the combustion chamber. Fig. 2 shows the pressure history of combustion chamber and the sequence of the events in the combustion chamber. The combustible mixture was ignited by a spark plug causing a pressure rise as shown in Fig. 2, and the initial reactants burnt to completion. Following the complete combustion of premixed gas, the combustion products were cooled down and this cooling-down period facilitates the necessary ambient conditions for diesel fuel injection. The ambient composition, pressure at the time of diesel fuel injection can be controlled by varying the composition of the premixture, and injection time relative to the pre-mixture spark timing, respectively. During the cool-down period, commercial ordinary diesel fuel was injected at specified timing that match with the required ambient conditions (1.36 MPa, in all experiments presented in this paper). The ambient temperature at the time of diesel fuel injection was calculated using ideal gas law with known density of in-chamber gases. After the injection of fuel, auto-ignition of the fuel occurred, the in-chamber pressure increased which resulted in second pressure peak in Fig. 2.

The fuel injection system was common-rail injection system with capability to do multi injection. Original 10 hole injector was modified to close all holes except one for the present experiments. Injector was centrally mounted in the combustion chamber, and oriented in such a direction that the spray from the nozzle directly interacts with the plasma plug that was located on the top-left of the chamber. Fig. 3 shows the configuration of the diesel injector, pre-mixture spark plug and microwave enhanced spark plug. The mass per injection from diesel fuel injector was measured in a separate experiment and averaged over 1000 injections. High-speed imaging to visualize the natural luminosity from diesel fuel combustion was conducted to make a qualitative comparison between different test conditions. A camera exposure time of 25 μs was used with 100 mm focal length lens, with aperture set at f8, and frame rate of 40000 FPS.

The microwave-enhanced plasma system is composed of a J-shaped non-resistive spark plug and a mixer unit containing a high voltage transmission line and a microwave transmission line (3). The initial arc/plasma was generated by a high voltage breakdown process similar to that which occurs in a regular spark plug. The resulting spark was enhanced in volume by using the microwaves supplied at 2.45 GHz frequency. The spark zone was exposed to microwaves after a 50 μs delay from spark. As the characteristics of microwave-enhanced plasmas vary with the microwave oscillation pattern; the microwave oscillation pattern was fixed at 1 μs pulse with a 50% duty cycle and a peak input power of 1600 W. The duration of the microwave exposure
following the spark triggering event was varied to achieve different plasma interaction times with spray.

A stub tuner was used to minimize the MW power reflection from plasma plug. The plasma plug is oriented such a way that, plasma directly interacts with spray hitting the plasma plug. The start timing of the plasma was made in such a way that always plasma starts before the auto-ignition of the flame, so that it is easy to identify the effects of plasma on ignition delay. All experimental conditions were listed in Table 1. At each operating condition, experiment was repeated for three times to obtain ensemble-averaged data of pressure history.

3. Results and Discussions

3.1 Effect of Plasma-Spray Interaction Duration

For the first set of experiments, the plasma was created within the combustion chamber with plasma radiation started simultaneously with the diesel injection i.e. 0 μs after start of injection (aSOI). Microwave input duration was controlled to

| Table 1: Experimental conditions |
|----------------------------------|
| Ambient pressure before diesel injection | 1.36 MPa  |
| Ambient temperature               | 650 K     |
| Composition before diesel injection |           |
| O₂                               | 21%       |
| N₂                               | 57.5%     |
| CO₂                              | 9.25%     |
| H₂O                              | 12.25%    |
| Injection pressure                | 100 MPa   |
| Injection mass (main inj.)        | 9.2 mg (650 μs) |
| Injection (pre-injection)         | 3.2 mg (278 μs) |
| Plasma timing                     | 0 μs, 500 μs, 1300 μs aSOI |
| Plasma duration (np1)             | 1.2 ms, 0.7 ms, 0.5 ms, 0.2ms |
| Plasma duty cycle                 | 50% at with pulse duration = 1 μs (i.e. pulse width 0.5 μs) |
| MW input peak power              | 1.6 kW    |

![Fig. 4. The natural luminosity images from the diesel fuel combustion for the conditions: main-only combustion, main-only combustion with 700μs plasma interaction time, main-only combustion with 1200μs plasma interaction time, double injection with additional pre-injection from top to bottom rows respectively. The time at which the image was captured relative to start of main injection was given at the top of each image in first row. Plasma appearance is annotated with ‘P’ for plasma cases. The view field is annotated with gray-dotted circle in each image.](image-url)
obtain the plasma-spray interaction time of 200 µs, 700 µs and 1200 µs.

Triggering for the fuel injection was started at 0 ms, however actual spray injection occurs after a certain delay which associate with the injection current profile. All the timings quoted in the manuscript were referenced to the electronic triggering of the fuel injection (0 ms). The time taken for the spray to travel from injector to the plasma plug was 300 µs, as measured from the high speed movies. It should be noted that plasma generation started at 0 µs aSOI, hence to get 700 µs duration of spray-plasma interaction, the total plasma radiation time should be set at 1000 µs.

Fig. 4 shows the history of natural luminosity images from the diesel combustion for different cases tested. The top row of Fig. 4 shows the main-only injection condition. The first luminosity signal was seen around 2.5 ms after start of injection (aSOI). Spray was not visible in earlier timings, as there was no light to illuminate the spray for imaging. Second row of Fig. 4 shows the images of diesel combustion with 700 µs duration of plasma interaction with spray. On the top left of the image at 0.25 ms aSOI, the plasma can be seen. The first appearance of the combustion luminosity was seen at 1.5 ms aSOI. For the 1200 µs plasma interaction case, the plasma existed for long time as evident by appearance of plasma event at 1.25 ms aSOI. However, the diesel soot luminosity was observed earlier in 1200 µs case compared to 700 µs case and main-only combustion. The images in the last row represent the combustion from main and pre-injection. As expected, the ignition delay was reduced and can be seen by early appearance of flame at 1.25 ms aSOI, for double injection.

For quantitative evaluation of the effects of plasma, heat release rates were computed for all the tested cases using one-dimensional heat release rate (10) ignoring the heat loss to walls. Computed heat release rates are shown in Fig. 5 for all the tested conditions. Compared to main-only combustion, 200 µs plasma case shows the earlier heat release. With the presence of plasma, low temperature chemistry of diesel was enhanced and the plasma induced radicals had its’ effect on the initial chain branching reactions during the low-temperature oxidation phase, which resulted a reduction in ignition delay (8). With increase in interaction time between plasma and spray, the ignition is further advanced, resulting in much shorter ignition delay. With plasma cases, the peak heat release rate also decreased. The first peak in heat release rate profile for diesel combustion is driven by the amount of premixing (11). The lower peak in heat release rate with plasma-spray interaction cases is due to reduction in ignition delay which decreased the available time for fuel premixing. Consistent with the expected trend, the peak of heat release rate further reduced and timing is further advanced for higher plasma-spray interaction durations. A comparison of plasma induced ignition enhancement against the double injection can be made using Fig. 5. A pre-injection amount of 3.2 mg was injected 800 µs before the start of main injection, keeping the main injection amount constant.

It should be pointed that, the tested double injection is slightly different from pilot-injection that normally employed in diesel engines. In pilot injection case, the main injection happens at much higher pressure than pilot injection due to the pressure rise driven by piston compression. However, in present experiment, it was not possible to inject the fuel at higher pressure than that of
first/pre-injection, hence the effect of pre-injection could be slightly different from engine based studies. Despite that, in both engines and chamber studies, pre-injection helps in promotion of low temperature oxidation. As expected, double injection has lower ignition delay, and earlier peak heat release comparing with main-only combustion as shown in Fig. 5. The peak heat release rate was higher due to that additional amount of fuel was added in pre-injection which resulted in extra fuel burnt during the premixing burn phase.

Total heat release for all tested conditions of Fig. 5 was computed and is given in Fig. 6. Except the double injection case, all other conditions resulted in same total energy released, indicating that the plasma did not show considerable improvement in combustion efficiency. The higher total heat release of double injection case was due to additional amount of energy added in the form of pre-injection. The noticeable observation from this Fig, was the effect of fuel evaporative cooling on heat release rate. The liquid spray gets evaporated by absorbing the latent heat from the ambient charge, which reflects as a drop in heat release rate. The results in Fig. 6 indicates that the effect of evaporative cooling was evident and this effect is different between plasma cases and non-plasma cases (refer to close-up view of Fig. 6). Compared to main-only case, the drop in heat release rate was much less when plasma-spray interaction exists. It is believed that enhanced low temperature oxidation caused an increase in local temperature which counteracts the pressure drop that occur due to the evaporative cooling. The other possible reason could be increase in local temperature by convection heat from plasma to surroundings.

From the calculated total heat released, the ignition delay was computed. Ignition delay was defined as the time difference between start of main injection and the time at which 5% of total heat released. However considering the differences in total heat release between main injection and double injection cases, ignition delay was computed based on the 5% of total heat released from main-only combustion case. The results are shown in Fig. 7. Consistent with observations in Fig. 5 and Fig. 6, the ignition delay reduced with increase in plasma-spray interaction time. Based on the tested cases, it was clear that plasma can effectively replace pre-injection for ignition delay control.

### 3.2 Effect of Plasma Starting Time

An attempt was to made to understand the relative importance of plasma timing with respect to start of injection timing. A 700 μs plasma interaction time was selected and compared the two different plasma start timings of 0 μs and 500 μs after fuel start of injection. The heat release rate plots are shown in Fig. 8. Similar to previous results, the plasma interaction decreased the ignition delay, however the variation of the timing does not have any impact on the ignition delay. It indicated that whether plasma interacts with early part of the spray, or later part of the spray does not have significant effect on ignition delay at tested conditions.

### 4. Conclusions

Microwave enhanced plasma was applied to diesel spray combustion and tests were conducted in a pre-burn type combustion chamber to access the effects of plasma on ignition delay of diesel spray. Also, a comparison was made between plasma induced ignition delay reduction and pre-injection induced ignition delay reduction.
• The ignition delay decreases with increase in duration of plasma-spray interaction
• At tested conditions, plasma can be an alternative to pre-injection to control the ignition delay
• For ignition delay control, plasma-spray interaction duration has dominant effect than timing of plasma relative to injection timing

Acknowledgements
This article is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO), Japan.

REFERENCES
(1) Hotta, Y. et al., Achieving Lower Exhaust Emissions and Better Performance in an HSDI Diesel Engine with Multiple Injection, SAE Technical Paper 2005-01-0928 (2005).
(2) Werblinski, T. et al., Effect of Pilot Injection Timing on the Two-Stage Combustion Characteristics of Diesel and n-Heptane Studied in a Rapid Compression Machine, 7th European Combustion Meeting (ECM 2015), Budapest, Hungary (2015).
(3) Ikeda, Y. et al., Research and Development of Microwave Plasma Combustion Engine (Part I: Concept of Plasma Combustion and Plasma Generation Technique), SAE Technical Paper 2005-01-0928 (2005).
(4) Do, H. et al., Plasma assisted flame ignition of supersonic flows over a flat wall, Combustion and Flame, Vol. 157, No. 12, pp. 2298–2305 (2010).
(5) Ju, Y. et al., Plasma assisted combustion: Dynamics and chemistry, Progress in Energy and Combustion Science, Vol. 48, pp. 21-83 (2015).
(6) Ando, H. et al., Chemical Kinetics of Plasma-Assisted Combustion, Possibility of Ignition Delay Shortening by Plasma-Support. J. Plasma Fusion Res. Vol.89, No.4, pp. 220-224, (2013).
(7) Ju, Y. et al., Plasma Assisted Low Temperature Combustion, Plasma Chem Plasma Process, Vol. 36, pp. 85–105, (2016).
(8) Nagaraja, S. et al., Effect of non-equilibrium plasma on two-stage ignition of n-heptane, Proceedings of the Combustion Institute, Vol. 35, pp. 3497–3504, (2015).
(9) Ikeda, Y. et al., Microwave Enhanced Ignition Process for Fuel Mixture at Elevated Pressure of 1MPa, 47th AIAA Aerospace Sciences Meeting, January 2009, Orlando, Florida
(10) Padala, S. et al., Ethanol utilisation in a diesel engine using dual-fuelling technology, Fuel, Vol. 109, pp. 597–607 (2013).

(11) Heywood JB., Internal Combustion Engine Fundamentals, London, McGraw-Hill, 1988.