Influence of Laser Incident Angle on Laser Breakdown-Assisted Long-Distance Discharge Ignition (LBALDI)

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We have developed a new volumetric ignition method called Laser Breakdown-Assisted Long-distance Discharge Ignition (LBALDI). In LBALDI, laser breakdown plasma is utilized to assist spark discharge by facilitating formation of ionization channel. It is expected to improve lean ignitability limit by long distance discharge for extended initial flame kernel, which was proved by our previous research. The authors investigated the influence of laser incident angle on the probability of discharge by LBALDI. It was found that discharge was the most successful when the incident laser was directed perpendicular to the discharge path.

Keywords: laser breakdown, spark ignition, laser breakdown-assisted long-distance discharge ignition, spark discharge, laser incident angle, discharge probability

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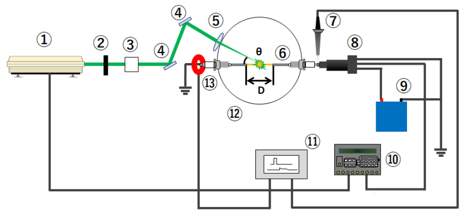
It is now increasingly required to improve fuel consumption characteristics and reduce pollutant emission in the exhaust gas. Therefore, lean burning is attracting attention for better thermal efficiency owing to higher specific heat ratio and reduced NOx emission by lowered combustion temperature. However, it also decelerates the flame propagation and therefore it is more difficult to ensure successful ignition. To advance lean-burning technology to a realizable level, more efficient methodology for ignition is required. The authors proposed a new ignition method called Laser Breakdown-Assisted Long-distance Discharge Ignition (LBALDI) which forms laser-breakdown plasma to assist spark ignition [1–5]. It produces laser breakdown plasma between electrodes applying a high voltage, by which it facilitates the formation of ionization channel between them [1, 2]. LBALDI realizes more volumetric ignition surpassing conventional spot laser ignition [6–9], which will contribute to stable lean-burning operation of spark-ignition automobile engine.

In our previous study [3, 4], spark ignition, laser ignition and LBALDI were compared in ignition probability of methane/air and propane/air mixture in a constant volume vessel for variable equivalence ratio, where LBALDI successfully extended lean ignitability limit compared to the other two conventional methods. Schlieren photography also proved extension of the ignition kernel opposite to the laser incident direction. The asymmetric behavior of the ignition kernel observed indicates there should be some relationship between laser incident angle and discharge characteristics/ignitability, which has not been clarified yet. In the present study, the authors investigated the dependence of discharge probability on the laser incident angle by varying the distance between the electrodes.

Schematic of the experimental step is illustrated in Fig. 1. Nd: YAG pulse laser GCR-200 (Spectra Physics) is irradiated with the wavelength 532 nm and pulse width 7 ns. Pulse energy was fixed to 45 mJ controlled by combination of lambda half-wave plate WPQG-5320-2M (SIGMAKOKI) and polarizing beam splitter PBSHP-15-5320 (SIGMAKOKI). Laser beam with beam diameter 9 mm was then focused through convex lens f = 150 mm to generate breakdown plasma on the center between electrodes. The electrode used was cylindrical in shape with 2.5 mm diameter, and 8.8 mm length. Rotation stage was used to rotate the electrodes around the laser focal spot to vary the laser incident angle 40, 90 and 140 degrees from the direction of the cathode (Fig. 2). The distance between the electrodes is also adjustable, and in this study was varied in the range 5 - 25 mm by increment 1 mm.

Commercial ignition coil 90919-02244 (DENSO) was



①Nd:YAG laser ②Crystaline quartz half wave plate ③Polaroid beam splitter ④Mirror ⑤Lens ⑥Spark plug ⑦H.V. Probe ⑧Igniter ⑨Battery ⑩Delay generator ⑪Oscilloscope ⑫Turntable ⑬Current probe

Fig. 1 Experimental setup.

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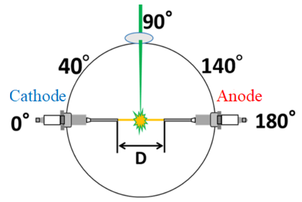

Fig. 2 Definition of laser incident angle.

used to generate high voltage with an automobile battery Blue Battery Caos (Panasonic) as a power source. A voltage probe P6015A (Tektronix) and a current probe CT-0.5-B (Bergoz) were installed to monitor voltage and current between the electrodes, which were sampled with an oscilloscope GDS3254 (Instek GW) for judging the success of the discharge.

In this study, the delay time Δt of voltage application on the electrodes from the laser irradiation was controlled with a delay generator DG645 (Stanford Research Systems). Charging time for the igniter was fixed to 3.2 ms to generate constant nominal discharge energy 20 mJ. In this study, the experiment was performed at a constant delay time Δt = 50 µs. This delay time was chosen according to the previous study [5] which proved the timing to minimize the discharge threshold voltage.

Experimental investigation of the discharge probability by LBALDI was done against ambient air and compared with spark discharge. Air condition was consistent through all the experiments at a temperature of 291.7K and a relative humidity of 30%. Care should then be taken to the point that LBALDI was implemented with total energy of 20 + 45 = 65 mJ/pulse. Discharge probability was evaluated through 30 trials for each experimental condition.

Relationship between the discharge probability and variable electrode gap for each laser incident angle is summarized in Fig. 3. Three colored plots denote the results by LBALDI at each incident angle 40, 90, 140 degree. The result by the discharge without laser incidence was shown by black plots for reference. It is apparent that the discharge probability was notably increased by addition of laser breakdown plasma, which again elucidated the validity of LBALDI as a useful method for extending discharge distance. Comparison at constant total energy deposition in our previous study [3, 4] already proved LBALDI to be more efficient in ignition than by spark discharge alone. For all the three incident angles, the probability radically changed from zero to 100% in a narrow range of the electrode gap ∼5 mm. The probability at the incident angle of 40 and 140 degree, which is the same in the inclination from each electrode, showed a similar dependence. However, at the incident angle of 90 degree, the probability barely exceeded the other two incident angles to extend discharge distance roughly about by 2 mm. According to the literature on laser ignition [6–9], initial flame kernel is far from spherically symmetric forming 'third lobe' extending linearly to the incident direction and toroidal ring structure expanding perpendicular to the incident direction. This asymmetric behavior was also confirmed by our previous study on LBALDI [3, 4], which should be one explanation for the dependence on the incident direction. It is interesting to note here that optimal direction for discharge may exist out of that parallel to the extension of ignition kernel.

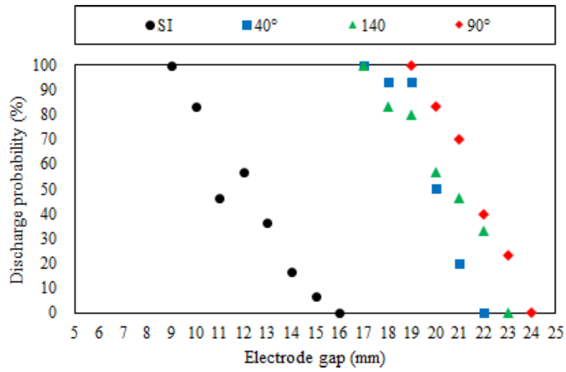

Fig. 3 Variation of discharge probability against electrode gap at each laser incident angle: Black plots denotes the result of spark ignition (SI), and colored ones are those of LBALDI.

To provide conclusive discussion on the findings described above, the experimental method needs improvement to adjust the pressure and moisture containment of the air by supplying dry air to a closed vessel for a more sophisticated evaluation of the probability, excluding the influence of the air condition. Also, high-speed visualization of the process of spark formation will render an important perspective.

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