

Dual-Point Laser Ignition and its Location Effects on Combustion in Lean-Burn Gas Engine

Seiya Yamaguchi, Takashi Kashiwazaki, and Makihito Nishioka
University of Tsukuba

Eiichi Takahashi, Hirohide Furutani, and Hirokazu Kojima
AIST

Jyunya Miyata
Mitsui Engineering & Shipbuilding

ABSTRACT

As a result of the excavation of unconventional sources of natural gas, which has rich reserves, has attracted attention as a fuel for use in natural gas engines for power generation. From the viewpoints of efficient resource utilization and environmental protection, lean burn is an attractive technique for realizing a higher thermal efficiency with lower NOx emissions. However, ignition systems have to be improved for lean-burn operations. Laser ignition, which is expected to serve as an alternative to spark plug ignition, can decrease the heat loss and has no restriction on the ignition location because of the absence of an electrode.

Consequently, an extension of the lean-burn limit by laser ignition has been demonstrated. In this study, we investigated the effects of the location and number of laser ignition points on engine performance and exhaust emissions. Laser ignition was also compared with conventional spark plug ignition. The investigation was conducted using a single-cylinder NA gas engine, which used CH₄ for fuel. The results showed that the use of two-point laser ignition can extend the lean-burn limit compared to two-point spark plug ignition or single-point laser ignition. In addition, the laser ignition achieved a higher thermal efficiency with lower NOx emissions than two-point spark plug ignition.

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INTRODUCTION

As a result of the excavation of unconventional sources of natural gas, which has rich reserves, is expected to be used as a fuel in natural gas engines for power generation. Natural-gas-fueled small and mid-sized engines are used for cogeneration in the consumer and industrial sectors. The lower NOx emissions and better fuel consumption of gas engines are important for environmental protection and the efficient use of resources. Therefore, recent gas engines have operated under lean-burn or exhaust gas recirculation (EGR) conditions. However, a leaner or highly diluted mixture can also cause misfires, resulting in poor thermal efficiency [1] [2]. An enhanced ignition system, as an alternative to the conventional spark plug system, is required to solve these problems.

Hence, many types of ignition systems have been investigated. A pilot ignition system (diesel dual fuel) is known to have a higher ignition capability than conventional spark plug ignition. This system uses a liquid fuel with a high cetane number as the ignition source

[3], along with a pre-chamber plug [4], which causes ignition at a small cavity in the device tip. Some practical gas engines are already equipped with this type of ignition system.

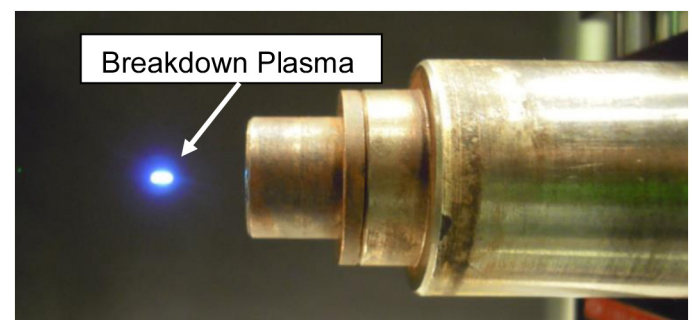


Figure 1. Laser Breakdown Plasma

Laser ignition has attracted attention as another alternative ignition method. In laser ignition, a high-temperature breakdown plasma generated by a focused laser beam is used as the ignition source, as shown in Fig. 1. Laser ignition has two main features that make it

different from a conventional spark plug system. There is no restriction on the ignition position and no heat loss to electrodes, which can prevent the development of the initial flame kernel. Furthermore, the fact that the minimum ignition energy of a spark plug is increased by increasing the in-cylinder pressure is widely known. In contrast, it is known that the minimum ignition energy of laser ignition is decreased by increasing the in-cylinder pressure [5]. Moreover, because CH_4 , which is the main component of natural gas, has a high octane number, the compression ratio and boost pressure of a natural gas engine can be higher than those of a gasoline engine. Therefore in a natural gas engine, the above characteristic of the minimum ignition energy provides a great advantage for laser ignition.

In a prior study of a laser ignition engine, Dale et al. succeeded in operating a gasoline engine using laser ignition for the first time [6]. Based on the results of that study, laser ignition can extend the lean limit and realize lower NOx emissions compared to spark plug ignition. In addition, they also reported that laser ignition had a higher ignition capability than spark plug ignition under EGR conditions.

Srivastava et al. investigated the effect of the ignition location on the exhaust emission and fuel consumption of a natural gas engine by changing the laser breakdown location along a single optical path [7]. The results showed that the ignition location did not significantly affect these characteristics. However, in this study, the ignition location was changed only along the center line of the chamber. Therefore, the effects of ignition at peripheral locations on the engine performance and exhaust emissions were still uncertain. As shown in previous reports [8] [9] on spark plug ignition, it may be possible to use off-center ignition to gain a shorter combustion duration as a result of swirl flow.

Using a natural gas engine, Richardson et al. reported that laser ignition had a knock limit similar to spark plug ignition, and the lean limit of the laser ignition was clearly extended [10]. However, the thermal efficiency was degraded in the leaner region near the flammability limit, even in the case of using laser ignition. If this problem was caused by a poor burning velocity [11], multi-point laser ignition will solve this problem. Phouc [12] and Morsy et al. [13] already reported that multi-point laser ignition can realize a shorter combustion duration than single-point laser ignition in a constant-volume vessel. However, the effects of multi-point laser ignition on an internal combustion engine have not been reported.

Thus, this study revealed the effects of the peripheral ignition location and two-point ignition using a laser or spark plug on the exhaust emission and performance characteristics of a lean-burn natural gas engine.

EXPERIMENTAL

Figure 2 shows a schematic of the experimental equipment. The test engine was a single-cylinder 4 stroke NA gas engine, which was based on a 4-stroke diesel engine (Yanmar: NFD-170). It has a bathtub-shaped chamber, and a bore and stroke of 102 mm and 105 mm, respectively. The displacement of the cylinder is 857 cc, with a compression ratio of 12.

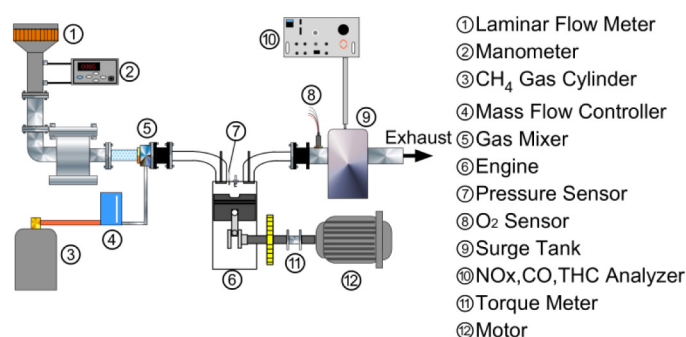


Figure 2. Schematic of Experimental Equipment

Air was mixed with CH_4 at the gas mixer, and this mixture was aspirated by the engine without throttling. Exhaust gas analyzers were used to analyze exhaust gas sampled from the surge tank, which contained an exhaust manifold. We used following types of exhaust gas analyzers CLD type for NOx measurement, NDIR type for CO measurement, and FID type for THC measurement. The sampling rate for the exhaust gas analysis was 1 Hz, and the total sampling duration was 60 s. The engine speed was set at 1200 rpm, and the ignition timing was set at the maximum brake torque (MBT). In this experiment, the equivalence ratio ϕ was adjusted from $\phi = 0.80$ to leaner, decreasing the fuel flow rate, to reduce the thermal load on the test engine. This experiment was conducted under the condition that the THC concentration in the exhaust gas was below 10000 ppmc.

A capacitive discharge ignition (CDI) circuit and J type sparkplug were used for the spark plug ignition. The input energy of the spark plug ignition was 20 mJ for the single-point ignition, and a total of 40 mJ for the two-point ignition. A frequency-doubled YAG laser with a pulse duration of 7 ns (Lotis TII LS-2134D) was used for the laser ignition. The laser beam passed through an open beam path and was introduced to the engine cylinder, as shown in Fig. 3. In the case of two-point ignition, the laser beam was split and introduced to an optical assembly holder, which contained a sapphire window and synthetic fused silica lens, mounted on the cylinder head.

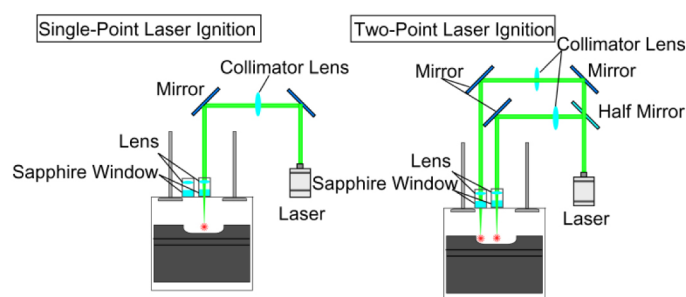


Figure 3. Optical Beam Path of Laser Ignition

RESULTS AND DISCUSSION

Effects of Laser Pulse Energy E_{in} on Engine Performance

First, the laser pulse energy E_{in} was varied to find the optimal value. The center of the chamber was used as the ignition location (defined as Center), as shown in Fig. 4.

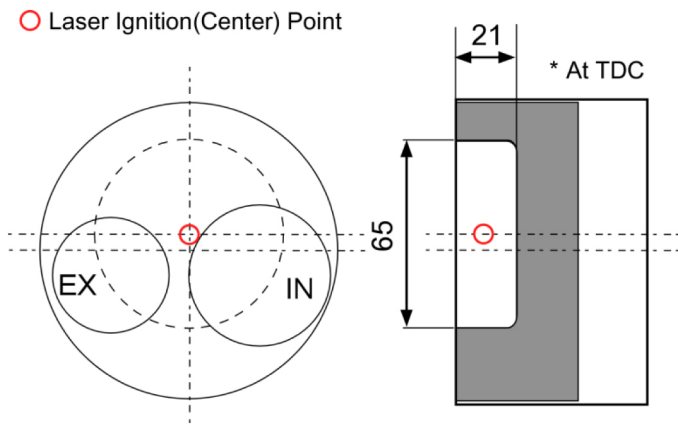
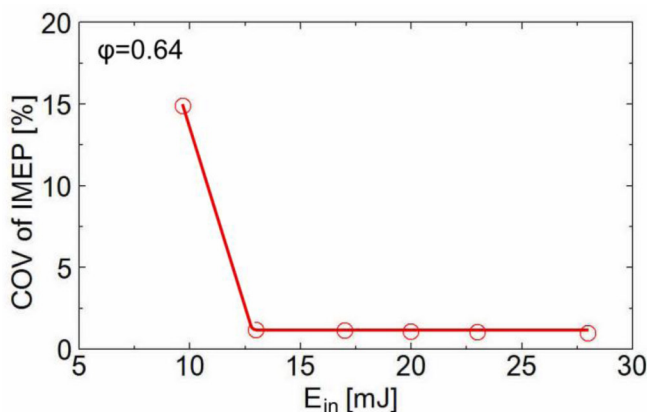
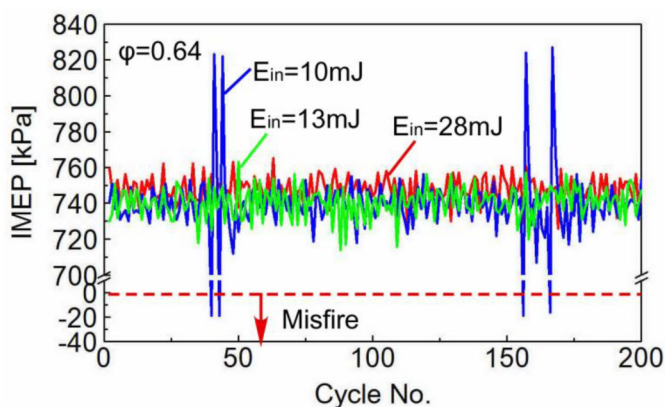


Figure 4. Ignition Location for Laser Energy Dependence

The values of ϕ and ignition timing T_{ig} were set at 0.64 and 14deg. BTDC, respectively. Fig. 5 shows the relationship between E_{in} and the coefficient of variation (COV) of the Indicated Mean Effective Pressure (IMEP). A pulse energy E_{in} larger than 13 mJ enabled stable operation, as shown in Fig. 5. However, a series of IMEPs for 200 cycles with $E_{in} = 10, 13$, and 28 mJ are shown in Fig. 6. In the case of $E_{in} = 10$ mJ, misfires ($0 > IMEP$) were observed. This was probably due to the pulse energy E_{in} being too close to the breakdown threshold. Only a 1% increase in the IMEP was gained by increasing E_{in} from 13 mJ to 28 mJ. Thus, decreasing E_{in} caused misfires, whereas an excess E_{in} only caused serious damage to the optical assembly. Moreover, it cannot be expected to significantly improve the thermal efficiency. Based on the results of this experiment, E_{in} was adjusted to 13 mJ in this study.

Figure 5. Effects of E_{in} on Stability of IMEPFigure 6. Effects of E_{in} on Cyclic Variation of IMEP

Effects of Ignition Location on Engine Performance

Next, we investigated the effects of the ignition position in the cylinder. The details of the ignition locations are shown in Fig. 7. We define the ignition position at the center of the cylinder as "Center" and the position close to the wall of the bathtub-shaped chamber as "Wall." In addition to the above locations, an ignition location just inside the optical assembly holder labeled "Gap" was also tested to obtain information about the combustion characteristics of a laser ignition location with heat loss and less charge motion, as shown in Fig. 8.

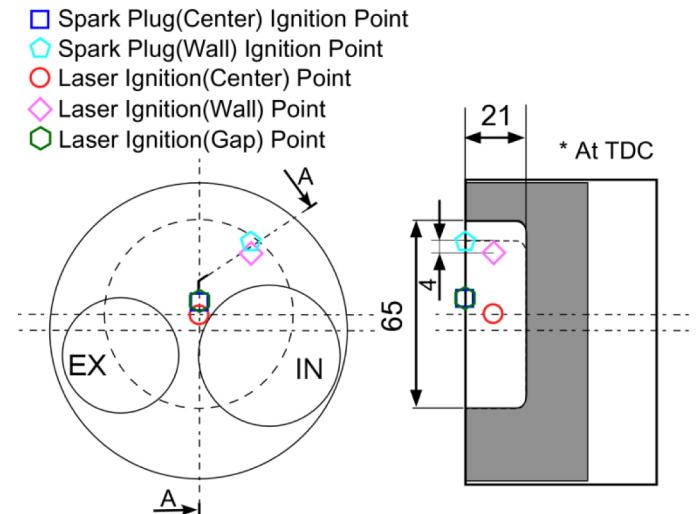


Figure 7. Ignition Locations in single-point ignition test

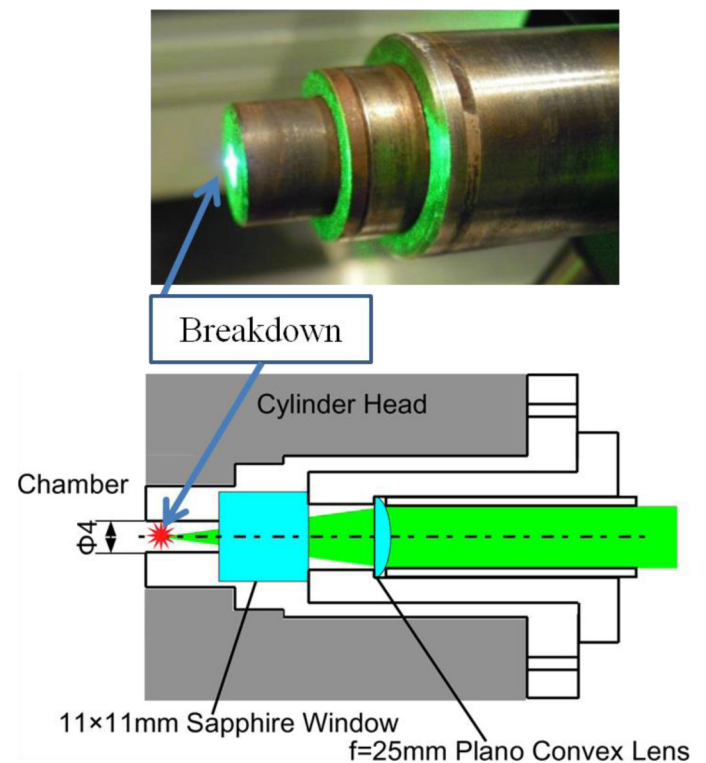


Figure 8. Breakdown Plasma and Ignition Location of Gap

The effects of the ignition locations on the pressure and heat release histories are shown in Fig. 9 and 10, based on the spark plug and laser ignition tests, respectively. When using Wall laser ignition, a slower pressure rise and heat release were observed, as shown in Fig. 10. This behavior was not seen for the case of spark plug ignition.

The difference is assumed to be the result of the exact locations of the laser and spark plug ignitions. The position of the “Wall” laser ignition was near the piston wall. Hence, heat loss from the initial flame kernel to the piston wall occurred. In the case of a stable combustion situation such as $\phi = 0.80$ or 0.65 , without using the Wall laser ignition, the differences in the pressure records due to the ignition types and locations were small.

Figure 11 shows the dependence of the COV of the IMEP and the indicated thermal efficiency on the equivalence ratio. Figure 11 shows that in both ignition methods, Wall ignition achieved a lower COV of the IMEP to a leaner area than Center ignition. When the ignition locations were the same, laser ignition realized a lower COV of the IMEP to a leaner area than spark plug ignition. Furthermore, the thermal efficiency suddenly deteriorated as the COV of the IMEP increased, regardless of the ignition type and location.

Next, the combustion duration was evaluated using the mass fraction of burned fuel (MFB). In this study, the combustion duration was divided into three periods, as shown in Fig. 12. First, the heat release delay, which was the period from the start of inputting energy to the initial flame kernel formation, was defined as the period from ignition timing T_{ig} to the crank angle for an MFB of 5%. Second, the middle stage of combustion was defined as the period when the MFB was 5%-20%. Third, the end stage of combustion was defined as the period when the MFB was 20%-90%, and these durations were also evaluated. Fig. 13 shows the relationship between ϕ and these combustion durations when using the spark plug and laser ignitions under the condition that no misfire occurred.

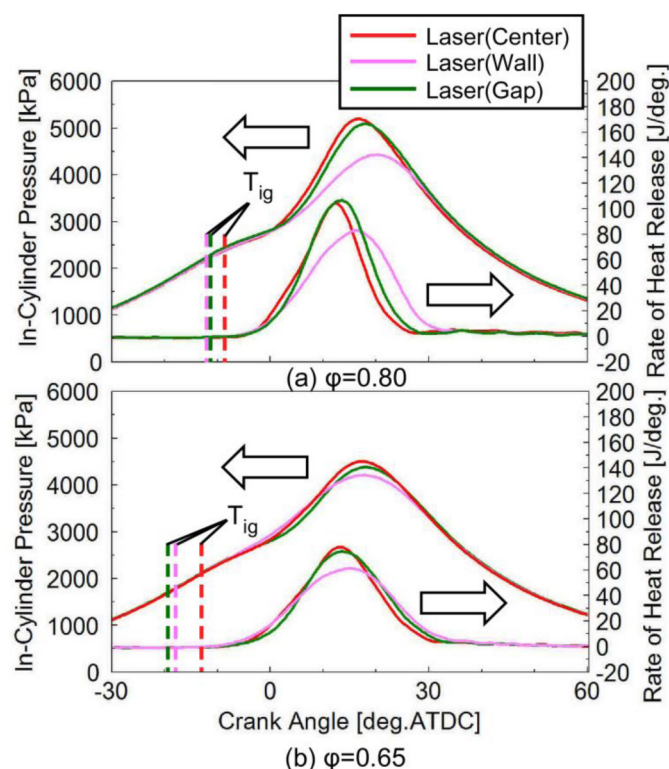


Figure 10. In-Cylinder Pressure and Heat Release (Laser Ignition)

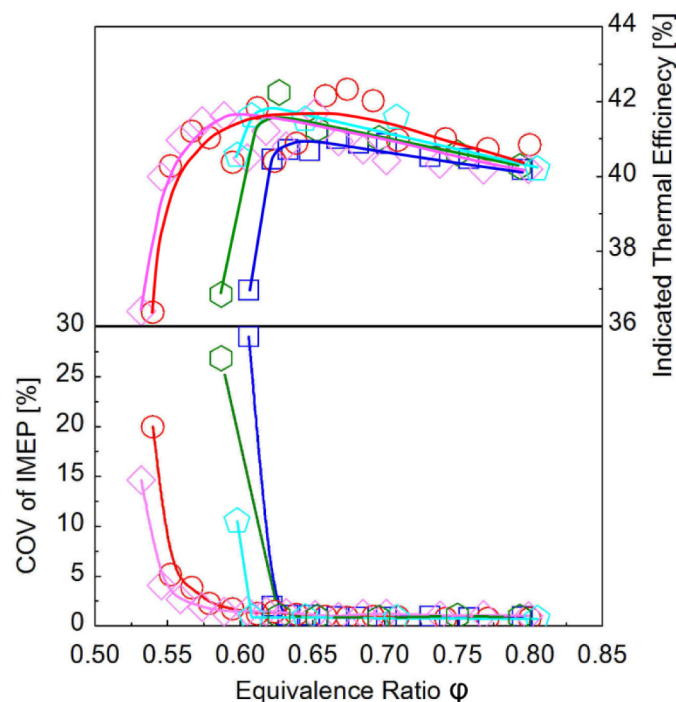


Figure 11. IMEP Stability and Thermal Efficiency of Each Ignition Type and Location

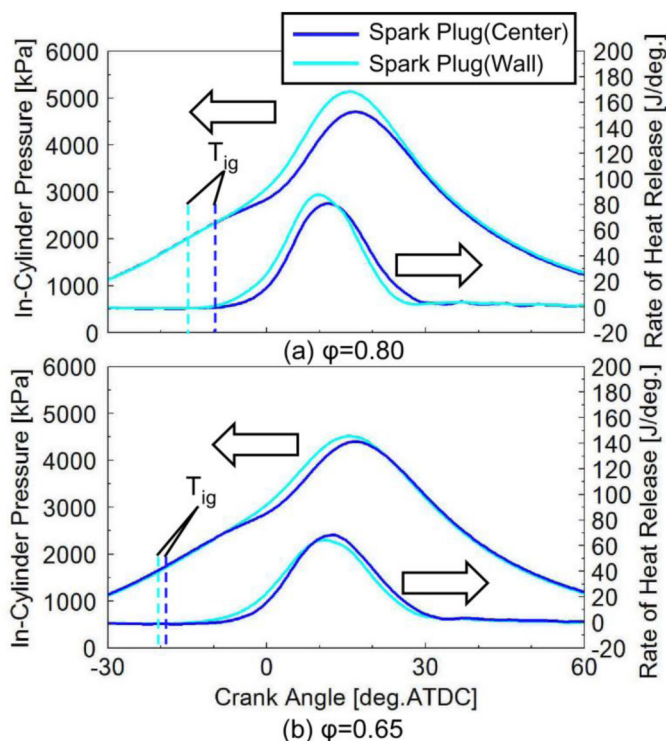


Figure 9. In-Cylinder Pressure and Heat Release (Spark Plug Ignition)