Advanced ignition technology for the achievement of high thermal efficiency of internal combustion engine

— A demonstration of laser ignition in natural gas engines —

Eiichi TAKAHASHI[1]*, Hirokazu KOJIMA[2] and Hirohide FURUTANI[2]

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Natural gas engines have been attracting a lot of attention recently due to the development of unconventional natural gas sources. Achieving lean burn with supercharging is necessary to attain high thermal efficiency. Conventional spark plugs face difficulties with ignition because of the high pressure and lean air/fuel mixture. This paper describes studies on laser spark ignition which has been investigated at AIST as an alternative method for the achievement of stable ignition under such conditions. The extension of lean limit and improvement in thermal efficiency are demonstrated, and the possibilities of advanced laser ignition are also discussed.

Keywords **:** Natural gas, lean-burn, supercharging, laser ignition, thermal efficiency, cogeneration

1 Introduction

Unconventional natural gas resources have been developed recently all over the world because of advances in mining technology. The total natural gas reserve including reserves present in unconventional mines is estimated to exceed 200 years, and these mines are distributed globally.[1][2] Compared to the usual liquid fuels, natural gas has higher hydrogen-to-carbon ratios in its molecules, and it produces fewer carbon dioxide emissions per unit of calorific value. Furthermore, the sulfur content in natural gas is very small, and it has therefore attracted interest as fuel for marine engines to enable them to adhere to recently developed exhaust gas regulations.[3] Therefore, the role of natural gas is expected to increase in importance as a major energy source.

Natural gas is also used as a fuel for cogeneration (combined heat and power), which produces not only electricity but also heat. Therefore, its total efficiency is high. However, according to a report published by the American Council for an Energy-Efficient Economy (ACEEE) titled “The International Energy Efficiency Scorecard,” Japanese buildings have a low energy-utilization efficiency and the use of cogeneration is little.[4] Therefore, cogeneration is expected to improve this situation.

There are several types of cogeneration alternatives, such as fuel cells, gas turbines, and gas reciprocating engines. Gas engine cogeneration ranges in scale from being compact for family use to large for industrial applications, and there is therefore a large number of installations. The electrical power efficiency of the latest gas engine was a lower heating value (LHV) of almost 50 %. This is because of the application of technologies such as lean burn and mirror cycles.[5]

Even though cogeneration has a high total energy-utilization efficiency, the practical application of conventional cogeneration is suitable for cases that require a relatively large amount of heat because the proportion of heat obtained from cogeneration is still large. In general, electricity is a preferred product than thermal energy. Therefore, it is important to increase the thermal efficiency for electrical power generation to accelerate the adoption of cogeneration technology.

2 Technological issues affecting natural gas engines

2.1 Thermal efficiency of gas engines and future direction of technological development

The improvements in the thermal efficiency of gas engines are important for the promotion of gas engine-based cogeneration installation. Obviously, the maximum thermal efficiency is limited by the Carnot cycle according to thermodynamics. The actual gas engine is an irreversible engine, and the Otto cycle model, which is closer to a real engine, is used to understand its fundamental behavior. In the Otto cycle, fuel is supposed to burn at the location of the piston’s top position, which corresponds to the maximum compression. On the contrary, it is supposed to be exhausted at the bottom piston position, which corresponds to the maximum expansion. The thermal efficiency of the Otto cycle η_{th} is expressed in the following equation:

1. Research Institute for Energy Conservation, AIST Tsukuba East, 1-2-1 Namiki, Tsukuba 305-8564, Japan *E-mail: eiichi-takahashi@aist.go.jp, 2. Fukushima Renewable Energy Institute, AIST 2-2-9 Machiikedai, Koriyama 963-0298, Japan

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$$\eta_{th} = 1 - \left(\frac{1}{\varepsilon}\right)^{\kappa-1}$$

Here, ε is the compression ratio, and κ is the specific heat ratio, which is the ratio of the specific heat at constant volume and constant pressure. According to this equation, the relation between the thermal efficiency and the specific heat ratio is as shown in Fig. 1. As can be seen, the higher the compression ratio and the specific ratio, the higher the thermal efficiency becomes. With respect to the compression ratio ε, even though the natural gas is less likely to realize abnormal combustion, too large compression value leads to greater heat loss and/or abnormal combustion; thus, the practical value of the compression ratio is limited to around 14.

On the other hand, each molecule has its own specific heat ratio. Nitrogen and oxygen molecules, which are major constituents of air, are both diatomic molecules, and these have three translational degrees-of-freedom and two rotational during motion. The specific heat ratio of these is κ~1.4 around room temperature. Fuel molecules such as methane are polyatomic molecules. The specific heat ratio is around 1.3 because the molecules have more degrees-of-freedom during motion. Therefore, the total specific heat ratio of the air/fuel premixture is determined by the mixing ratio of air and fuel. Thus, we can increase the specific heat ratio by leaning out the premixture. Furthermore, the specific heat ratio decreases with increasing temperature because of the increase in the number of degrees-of-freedom, which better distributes the heat energy. Decreasing the temperature by the lean combustion is also effective to maintain a high specific heat ratio.

Thus, lean combustion and exhaust gas recirculation (EGR) are used to decrease the combustion temperature in order to improve the thermal efficiency. However, the consumption of fuel for each cycle decreases by simply leaning out the mixture, and the output power decreases. In order to compensate for this, turbo boosting is also employed. Recent compression end pressures that have been realized are almost 10 MPa (almost 100 atm). The recent technological trends in brake mean effective pressure (BMEP) and equivalence ratio is shown in Fig. 2. The equivalence ratio ϕ = 1 corresponds to the stoichiometric reaction of fuel and oxygen in air. A major trend of the technology is leaning out and boosting out to increase the BMEP. This increase in the BMEP also causes knocking, and leaning out is likely to result in misfiring. Thus, it is necessary to go through the “corridor” between the knocking and misfiring. Ignition devices have to realize stable ignition under this high pressure and lean premixture.

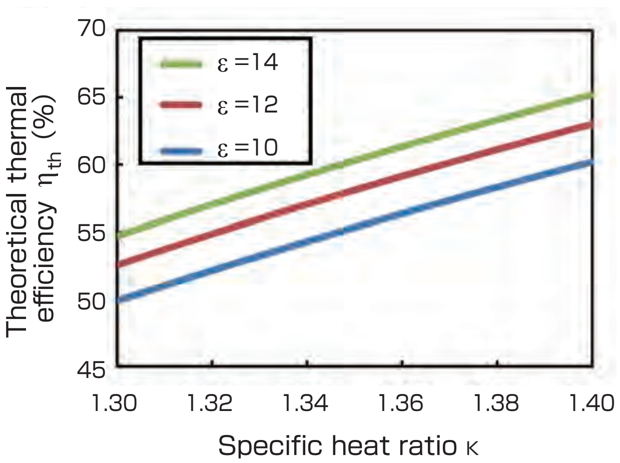

Fig. 1 Relationship between the specific heat ratio and the thermal efficiency of the Otto cycle

2.2 Problems of conventional ignition method: spark plug

The commonly used electrical spark ignition method is an ignition method that was invented more than 100 years ago. In spark plugs, discharge plasmas are formed between the high voltage and grounded electrode, and this causes ignitions to take place. Even though there have been continuous efforts to improve spark ignition, spark plugs are approaching their technological limit based on recent technological trends that see high boosting and lean burn.[6]

To generate discharge plasma, it is necessary to increase the number of electrons between the electrodes by accelerating them to form electron avalanches. Electrons in air obtain energy by accelerating in the mean free path of surrounding neutral molecules. These accelerated electrons collide with neutral molecules, thereby ionizing them. As the number density increases, the electron mean free path also shortens. Thus, to have sufficient ionization energy, the strength of the electric field also has to increase to compensate for it. In other words, in principle, the discharge is scaled by E/N (E: Electric field strength, N: Number density). Considering

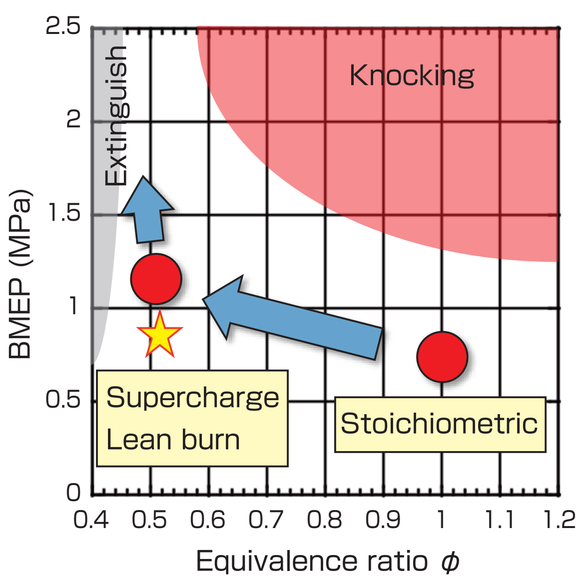

Fig. 2 Technology trends expressed in output as brake mean effective pressure and the equivalent ratio of the premixed gas

the supercharging of engines in the near future, this is a disadvantage for conventional spark plugs because it is necessary to increase the discharge voltage, which will cause not only shorter plug lifetimes, but will also lead to problems related to the dielectric insulation in many parts.

2.3 Alternate advanced ignition technology: laser ignition

Research that involves the use of pulsed laser for the ignition of combustible mixtures has been conducted in institutes worldwide, including the Mechanical Engineering Laboratory (MEL), which was one of the former institutes of the National Institute of Advanced Industrial Science and Technology (AIST) in Japan.[6][7] Schematics of engines that use conventional spark plug ignition and YAG laser ignition are shown in Fig. 3.

In laser ignition, laser pulses are focused by a convex lens, and plasma is formed by the dielectric breakdown of the premixture, which achieves ignition. Both lasers and spark plug ignition utilize hot plasmas, but the physics behind their formation is different. Therefore, the influence of both ignition methods on future supercharging engines will be different.

Plasma formation in laser ignition goes through the following two-steps (Fig. 4). First, focused high-intensity laser pulses produce electrons in the focal region through multi-photon ionization of molecules, which will be the initial electrons of discharge. Then, these electrons efficiently absorb laser energy through the inverse Bremsstrahlung process.[8] Because these processes are faster in mediums with a larger number density, laser breakdown is easier in supercharged engines. One of the commonly asked questions regarding laser ignition is whether there is a maximum pressure at which laser plasma can ignite. Considering the plasma formation in water, which has a density that is more than 100 times larger than that of ambient air, lasers can form plasmas easily, but electrical discharge requires a higher voltage. This suggests that the pressure is almost no problem for laser ignition. Flame-kernel developments observed by fast cameras using laser and spark plug ignition are shown in Fig. 5. In the upper pictures showing the laser ignition, a donut-shaped vortex is formed and the flame propagates quickly. On the other hand, in the lower spark plug ignition, the flame propagation is slower, which is due to the heat loss to electrodes. In addition, a characteristic vortex, which works as a flame holder, is formed in laser ignition.

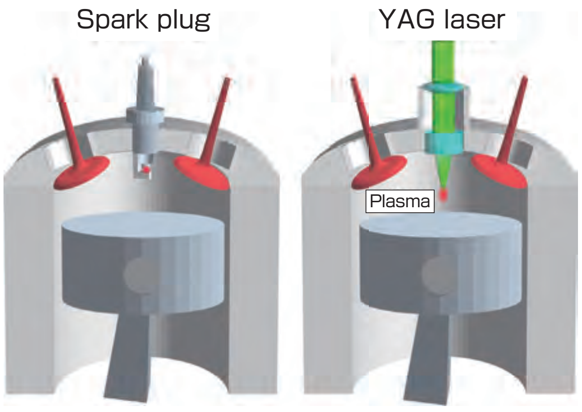

Fig. 3 Comparison between spark plug ignition and laser ignition in reciprocating engine

3 Scenario for the application of laser ignition in engines

In order to develop laser ignition for practical use, it is important to demonstrate the technical advantages, especially in supercharged engines, and the improvement in terms of thermal efficiency. Then, we can evaluate its feasibility based on the technological trends of gas engines. Furthermore, the degree of the improvement in the thermal efficiency enables us to estimate the payback time of any investment in this advanced ignition.

On the other hand, for general use, it is also important to consider the outlook of laser development with respect to the development of more compact, stable, and low cost laser devices. Long-term stability is essential, especially for cogeneration engines, because it will operate continuously for many months. The cost of the laser can be cheaper than that of engines for middle-to-large size cogeneration;

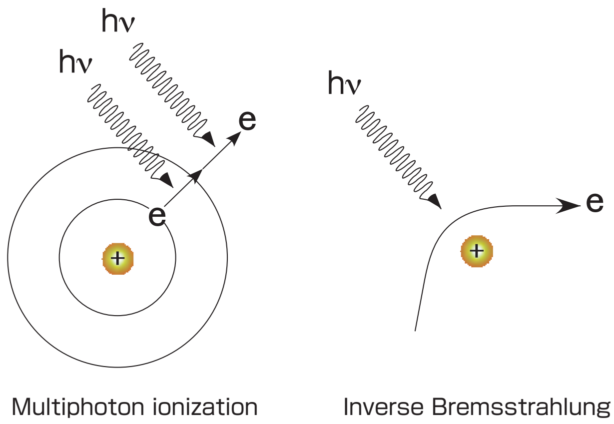

Fig. 4 Laser breakdown formation processes (multi-photon ionization and inverse Bremsstrahlung)

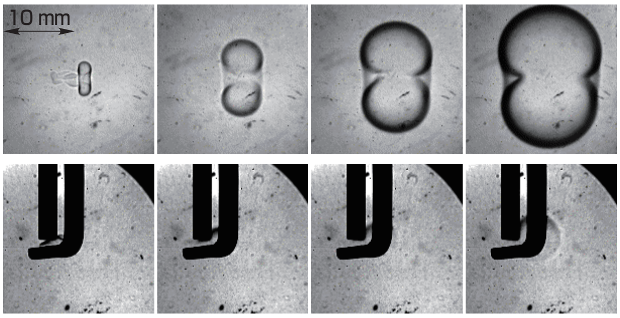

Fig. 5 Temporal flame-kernel development for laser and spark plug ignition

therefore, the cost may be recovered by the reduction in the fuel cost. In any case, as the price of the laser decreases, it is expected that it will be more widely used.

Figure 6 shows a diagram that represents the temporal progress of laser ignition research at AIST, the development of non-conventional natural gas resources and gas engines, and the revolutions of laser technology. This diagram also shows the outlook of laser ignition considering the relation between problems and progresses. Individual technologies and details of the demonstration experiments will be described in the following sections.

3.1 Innovation in the development of compact laser devices

Laser ignition research has been conducted at AIST since the days of the former research institute, MEL, and included laser ignition using photochemical reactions[9][10] and dielectric breakdown formed by laser pulse focusing.[11][12] For practical use, both a demonstration of the advantages of laser ignition, which has been achieved partly at AIST, as well as the realization of several innovations using laser devices are required. Because conventional lasers are precision instruments, they lack stability and durability and moreover, they are expensive as ignition devices. Therefore, improvements in the energy efficiency and possible continuous operation time of laser systems were indispensable. In this regard, replacing conventional flash lamps for laser excitation with laser diodes enabled more long-term operation, which also improved the energy efficiency from less than 1 % to around 10 %.

Next, an important issue to be resolved was the long-term stability and outlook with respect to reduced cost. These problems were solved by fabricating microchip composite lasers.[13][14] Conventional solid-state lasers used laser materials that are obtained by crystal growth. However, it was demonstrated that ceramics created by sintering can be used as optical material by sufficiently increasing the density to suppress the scattering from the grain boundaries. Furthermore, Taira developed a composite ceramics laser that contains a laser-medium, saturable absorber for Q-switch operation, and a mirror. A picture of the laser is shown in Fig. 7. A comparable laser size relative to that of spark plugs

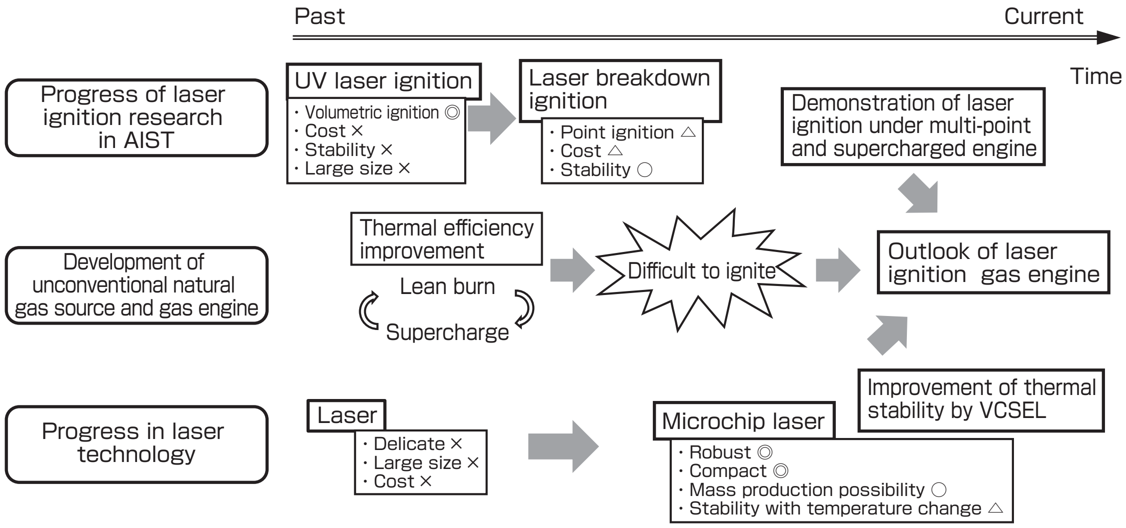

Fig. 6 Scheme and relationship of time evolution for each technology related to laser ignition of gas engine

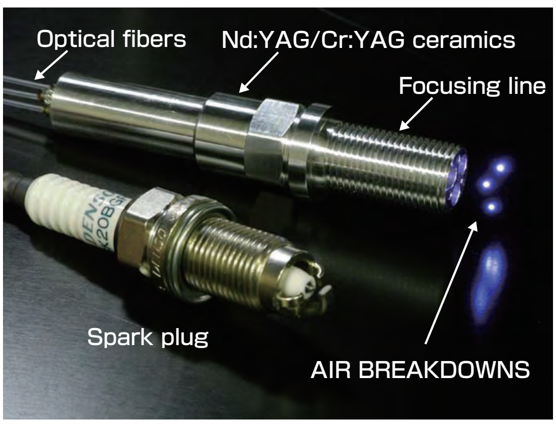

Fig. 7 Microchip laser[14]

Table 1. Specifications of the test engine

Base engine	NFD170
Type of engine	Four stroke
Bore × stroke (mm)	102×105
Displacement (cm³)	857
Compression ratio	12,14
Fuel	Methane
Rotation speed (rpm)	1200
Ignition timing	MBT
Swirl number	2.15~2.45
Maximum pressure (MPa)	8

has been realized. Innovations such as miniaturization and integration have increased the attention on laser ignition as a feasible technology.

3.2 Demonstration of laser ignition advantages in highly supercharged gas engines

It has been necessary to demonstrate the advantages of laser ignition over conventional spark plugs for recently developed supercharged gas engines. Here, we introduce the experimental results obtained by joint research between AIST and Mitsui Engineering & Shipbuilding Co. Ltd.

Figure 8 shows the experimental layout of the demonstration experiment involving a gas engine. We used a modified diesel engine, and compressed air was introduced from the compressor. Other parameters of the engine are listed in Table 1.

Because the maximum cylinder pressure of the engine is 80 atm., the intake-supercharged pressure was limited to 1.8 atm. The main result of the demonstration, which is the relation between the indicated mean effective pressure (IMEP) (not including mechanical losses) and the equivalence ratio, is shown in Fig. 9. The horizontal axis represents the equivalence ratio and the left side of the figure is leaner. The vertical axis corresponds to the output from the engine. The spark plug and laser ignition results are represented by square and circle points, respectively. Data in normal aspiration, without supercharging, are indicated as hollow characters, and the colors, which are listed as a table in the figure, represent the intake pressure. For normal aspiration experiments, the laser results maintained higher IMEP compared to spark plug ignition. Then, for the case of supercharging, spark plugs that are represented as red squares rapidly shifted toward the rich side. This indicates that spark plugs cannot ignite for the premixture under high-pressure conditions.

On the other hand, it has been demonstrated that lasers can maintain stable ignition even in the supercharged condition up to an intake pressure of 1.8 atm., which is the limit of the engine system.

3.3 Demonstration of improvement in thermal efficiency due to implementation of multi-point laser ignition in gas engines

In order to demonstrate the advantage of thermal efficiency improvement resulting from laser ignition, we conducted a dual-point laser ignition experiment using the same gas engine. The effect of the ignition on the coefficient of variation (COV) of the IMEP and indicated thermal efficiency are shown in Figs. 10 and 11, respectively. As can be seen in Fig. 10, the spark plug ignition rapidly becomes unstable below the equivalence ratio of 0.63 because of the unstable ignition. The lean burn limit is extended using laser

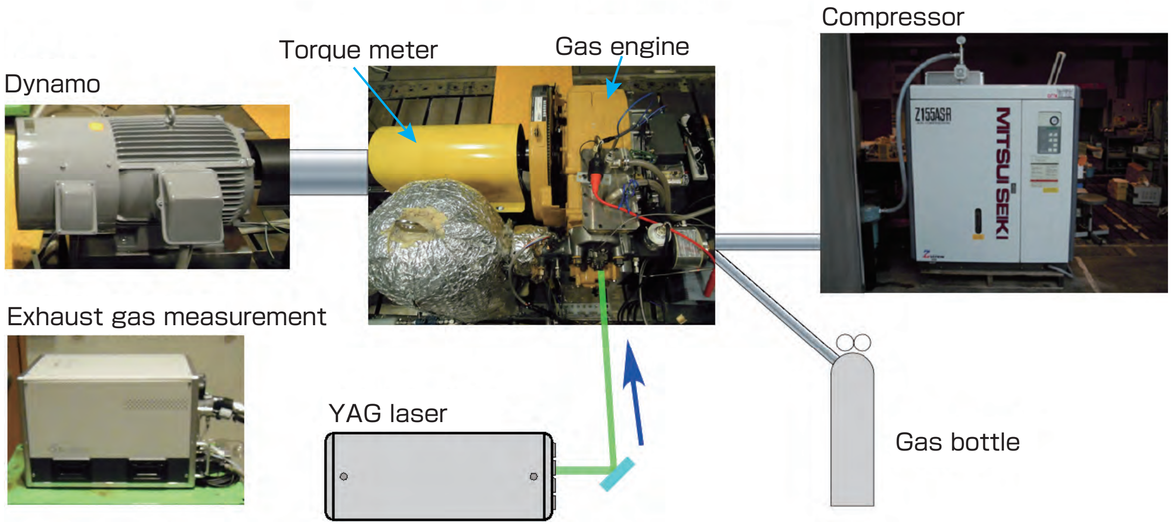

Fig. 8 Layout of demonstration experiment of laser ignited gas engine

ignition, which is represented as a red curve. Furthermore, the stable operation region of the equivalence ratio is also enlarged by the dual-point ignition.

A similar improvement is also observed in the thermal efficiencies. The dependence of the indicated thermal efficiency in Fig. 11 shows the improvement in all ignition methods when it is leaned out. However, for the case of the spark plug, a steep degradation was observed at an equivalence ratio of around 0.63, and this was due to the unstable ignition. On the other hand, for the laser ignition extension of the lean burn limit, the thermal efficiency increased. The main reason for this improvement is the fast formation of the initial flame kernel, which is attributed to the absence of heat loss to the electrode for laser ignition. Meanwhile, after the initial flame-kernel development, there is no difference between the single laser ignition and spark plug ignition methods with respect to the duration of the entire cylinder burn. Furthermore, double laser ignition achieved a shortening of the burning time after the initial kernel formation. This is due to the increase in the flame area, which enables an increase in the thermal efficiency.

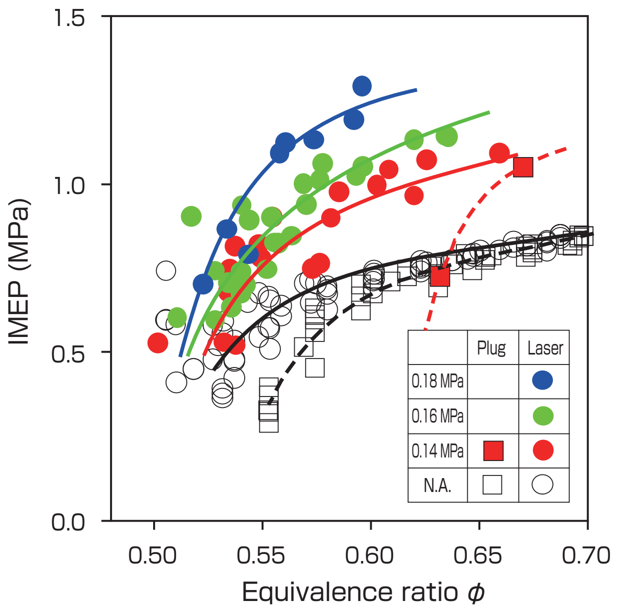

Fig. 9 Relation between the equivalence ratio and indicated mean effective pressure (IMEP) under the supercharging condition

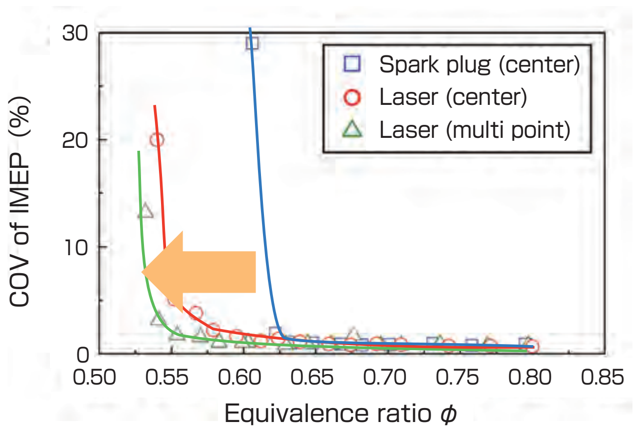

Fig. 10 Dependence of COV of IMEP on equivalence ratio

3.4 Exploration of advanced laser ignition for popular use

The required technologies for the application of laser ignition are listed in Fig. 12. Even though we aim at the use of laser ignition in large gas engines, the cost of the laser remains an important obstacle. Besides, there are many gas engine sizes, and the number of cylinders varies. There is a large cost difference depending on whether we can deliver the output of a laser system to every cylinder, or whether each cylinder requires a laser to ignite. The cost of current pulse lasers is of the order of several million yen, and this needs to decrease by several orders of magnitude. Meanwhile, the microchip ceramics laser that was mentioned in the former section is suitable for mass production, so a significant decrease in cost is expected if the market for the laser ignition increases with synergetic influences. Nevertheless, efforts to reduce the cost and improve the durability by reducing the required specifications are important, especially with respect to pulse energy. A further extension of the lean burn limit is still important. Therefore, we have to return to basic science to examine the breakdown process of the laser itself.

As described in a previous section, laser breakdown is caused by the multi-photon ionization and successive laser energy absorption through the inverse Bremsstrahlung process. Multi-photon ionization depends on the power of the

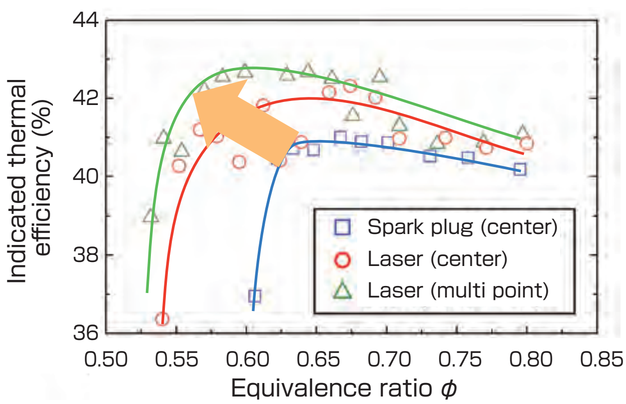

Fig. 11 Improvement of indicated thermal efficiency due to multi-point laser ignition

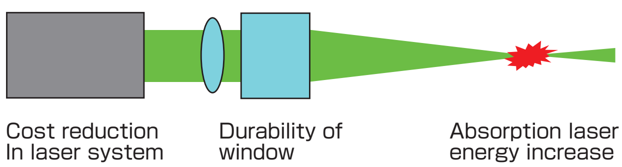

Fig. 12 Necessary technology for the development of laser ignition technology

focused laser intensity, so plasma formation is significantly affected by the laser intensity. The microchip-ceramics laser generates laser pulses with sub nanosecond pulse widths by employing short cavity Q-switch operation using a saturable absorber, and it generates laser pulses with high-peak power. The energy that is required to achieve ignition is obtained by the multi-pulse incidence. On the other hand, a common Nd:YAG laser generates laser pulses with pulse widths of several nanoseconds, which offers sufficient energy for easy ignition. However, the efficiency of utilizing laser energy for ignition is not very high because the intensity of the rising edge of the pulse is low and the multi-photon ionization is small. Here, we introduce several fundamental attempts to overcome these issues.

In order to separate the multi-photon ionization and inverse Bremsstrahlung processes, initial electrons were separately introduced in arbitrary time and space in order to observe the effect on the ignition. We used a Ti:Sapphire (TiS) laser, which can generate laser pulses with femto-second pulse widths, to generate the initial electrons. The pulse width of the TiS was 150 fs, so the peak power reached 1 GW even though the energy of the pulse was only 100 μJ, and we can use it to realize microlaser breakdown, which by itself cannot ignite the premixture alone. As shown in Fig. 13, to evaluate the influence of initial electron seeding, the TiS laser pulse was injected orthogonally to the YAG laser for ignition.

The absorption of the YAG laser was significantly influenced by the seeding, as shown in Fig. 14, which shows the relation between the incidence and absorption of the laser. The YAG laser requires around 35 mJ of energy to generate breakdown due to the pulse alone. By suppling the seed electron, the threshold decreased and the main YAG laser energy was absorbed very efficiently. Even for the lowest energy, the data point of the YAG energy for the dual laser in Fig. 14 was able to ignite the premixture.[15]

Images of the breakdown processes observed by a gated-intensified CCD camera are shown in Fig. 15. These pictures were taken with a 5-ns gate time and at 5-ns intervals. The relative position of the YAG laser-focusing beam and the TiS laser are in the leftmost picture. The TiS laser was focused at almost the center of the focal point of the YAG laser. The YAG laser pluses below the threshold of its breakdown alone were able to start breakdown by creating a slight ionization location. We also observed ionization wave propagation. The propagation velocity was estimated to be 10^5 m/s.[16]

Thus, we found that the YAG laser energy for the ignition may be significantly reduced by supplying initial electrons. In addition, the dependence of the absorption energy in Fig. 14 both with or without TiS have almost the same gradient over the range of energies of the incidence laser, which suggests the existence of an additional energy loss channel in the case without seeding electrons. Therefore, the lean burn limit can be extended using this method. However, it is not so practical when using the TiS laser, which is very complicated and delicate for ignition; therefore, we require simpler methods to supply electrons. One possibility is the combination of ultra-violet lasers, which merits further study.

In addition, the durability of the window for the laser incidence is another important technical issue to be resolved. Several papers have reported the accumulation of soot or deposits on the window, while others report the self-cleaning effect of lasers by the incidence of laser pulses with high fluence, which burns out the soot on the window or maintains the temperature of the window at a sufficiently high value to prevent the accumulation of deposits on the windows. In the experiments performed by our institute this phenomenon was not observed, but several potential reasons may be considered. Because the mechanism of its formation and

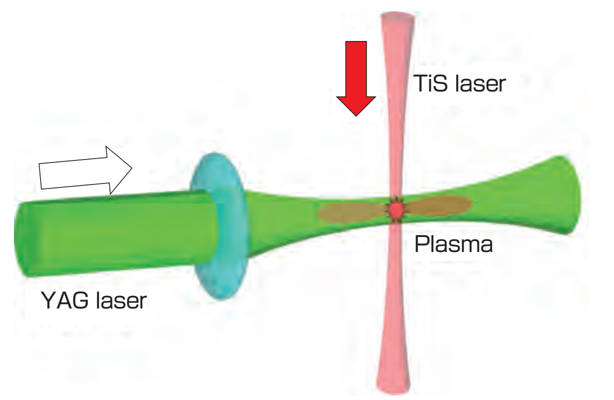

Fig. 13 Breakdown process of YAG lasers with initial electron

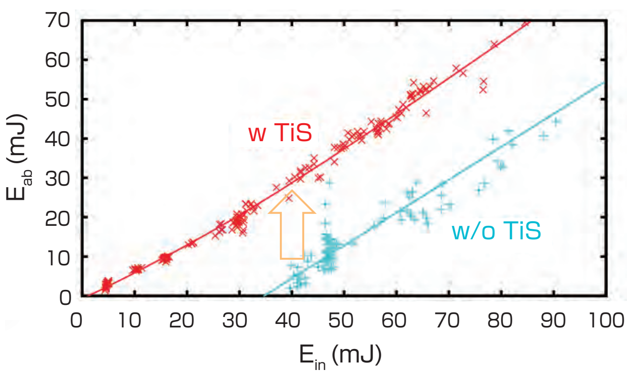

Fig. 14 Effect of TiS laser on the absorbed energy (E_{ab}) of YAG laser vs incident energy of the YAG laser (E_{in})

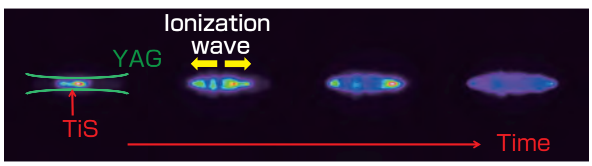

Fig. 15 Temporal breakdown process with initial electron supply

suppression methods is not established, it is necessary to carry out systematic research in this area.

In this review, we discussed the potential for the application of laser ignition for gas engines. The market for automobile engines is so large that the impact will be large if the ignition method is commonly used. However, there is a greater requirement for laser systems such as cost, size, and long-term stability. The potential for using a vertical-cavity surface-emitting laser (VCSEL), which has excellent temperature stability at its oscillation wavelength for the pumping of the microchip ceramics, was recently demonstrated.[17] It is expected that the use of laser ignition will be first applied to the cogeneration market, after which cost reductions will lead to development in other markets.

4 Summary

Because of the inherent advantage of laser ignition in high-pressure environments, it is attractive as an alternative ignition method for lean-burn supercharged gas engines. The innovations regarding laser systems, particularly with respect to its compactness, the use of composite configurations, and stability enable the widespread application of this method. In such an environment, demonstration experiments that show the advantage of laser ignition compared to conventional spark plugs have been conducted at AIST. In order to realize a more widespread acceptance and use of laser ignition, there is a need to realize a reduction in cost; therefore, we examined the potential for the application of the advanced laser ignition method, which was obtained from our fundamental investigations.

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Authors

Eiichi TAKAHASHI

Received doctorate degree in physics from Tsukuba University in 1994. Joined Electrotechnical Laboratory as researcher, where he engaged in laser fusion research. He has been involved in the application of laser ignition to internal combustion engines since 2009. His current research interests relate to the application of plasma to internal combustion engines, including laser ignition. In this paper, he demonstrated dual-point laser ignition and carried out experiments into the fundamental laser breakdown processes.

Hirokazu KOJIMA

Completed the doctorate course in energy science at the Graduate School of Energy Science, Kyoto University, in 2012. Since 2012, he has been a researcher at AIST. He has been engaged in research for engine combustion and highly efficient production and utilization of hydrogen energy carriers. In this study, he investigated the breakdown using a combination of a YAG laser and a TiS laser.

Hirohide FURUTANI

Joined Mechanical Engineering Laboratory at AIST after completing the doctorate course at the University of Tsukuba. He has studied laser ignition and control techniques for engine combustion for over 20 years. His interest is in realizing practical applications of laser ignition by carrying out more research and development into both engine combustion and laser technology. In this study, he performed experiments into supercharged gas engines, and showed the advantages of laser ignition.

Discussions with Reviewers

1 Overall paper

Comment (Akira Yabe, New Energy and Industrial Technology Development Organization (NEDO))

This paper discusses supercharging and lean burn as technological trends related to gas engines, and showed the advantages of laser ignition over the conventional spark ignition as a solution, together with a demonstration. The characteristics and effectiveness of laser ignition are also described systematically, and solutions to issues are offered. I think it is suitable for *Synthesiology.*

Comment (Hiroyuki Niino, AIST)

This paper synthesiologically describes the attempt to employ laser ignition as a substitute for conventional spark ignition to improve the thermal efficiency of internal combustion engines. In addition, the level of the research is high. I think it is suitable for *Synthesiology.*

2 Temporal arrangement of description of research progress in the paper

Comment (Hiroyuki Niino)

In each subchapter, technical obstacles are fully and clearly described. During its development, I assume there was technical progress from the initial stage, as associated technologies, equipment, and feedback from experts in other fields were applied. Therefore, to help the readers' understanding, it is preferable to consider the "synthesiological" scheme of the technological development including its differences with past, current, and future technologies including breakthroughs and serendipity.

Answer (Eiichi Takahashi)

Based on the suggestion made by the reviewer, we have included Fig. 6, which represents the progress of the entire combination of technologies. We hope that the demonstration experiment of laser ignition at AIST, as well as breakthroughs in laser technologies will contribute to overcoming obstacles in the development of future gas engines.

3 The dependence of thermal efficiency on ignition method

Comment (Akira Yabe)

Research on the performance improvement of spark plugs for future lean burn operation will continue. However, it is difficult to evaluate the technological advantages quantitatively although it can be assumed that there is small heat loss to the electrode and flame-holding by the vortex is effective.

It is desirable that this paper explains the following mechanisms. In Figure 11, for the thermal efficiency of spark plugs, lasers, and dual point laser ignition, the results should be on the same line after the equivalence ratio of 0.7. If there are possibilities of differences in thermal efficiencies, the mechanism or reason should be explained. Moreover, the reason for which dual point laser ignition provides better thermal efficiency than single point should be mentioned, at least qualitatively.

Answer (Eiichi Takahashi)

We thank the reviewer for that comment. As noted by the reviewer, the performance of spark plug ignition has continued to improve. By controlling the flow around the spark plug to lengthen the spark channel, we can suppress the heat loss to electrodes, as demonstrated by the laser ignition, and improve the lean ignition capabilities. However, the pressure will increase in the future because of the physical difference in the plasma formation, as described in the paper, and laser ignition has a clear advantage.

The reviewer expected to achieve asymptotic behavior on the spark plug and laser for an equivalence ratio of more than 0.7. We examined the temporal variation of the mass burning ratio, and the initial flame-kernel development is faster for laser ignition even at an equivalence ratio of 0.8. This, we think, brings about the difference in thermal efficiency. With respect to the difference between single and dual point lasers, flame area is double with the dual point than the single-point, and this contributes not only to the period of the initial flame-kernel formation, but also to the successive flame development thus shortening the combustion period. These mechanisms are added in the paper.

4 Progress of laser ignition research

Comment (Hiroyuki Niino)

Please consider the peripheral technology and research, which are necessary for research in the area of laser-ignition technology. Compared with the scenario above in Discussion 2, please indicate the remaining research issues that are required to fill the gap between the current and future technologies. These topics will be better understood if they are presented as a chart.

Answer (Eiichi Takahashi)

The most important obstacle for the practical implementation of laser ignition is the need to reduce the cost of lasers. We have added Fig. 12 to identify the research issues. We described a new method that was used to increase the fraction of laser energy absorption.

5 Spread and installation of laser ignition technology

Comment (Hiroyuki Niino)

The authors claim that the cost of lasers is most important for the widespread use of laser-ignition technology in society. Please discuss the prospects based on laser cost. Moreover, are there other similar issues to be solved? If so, please discuss them.

Answer (Eiichi Takahashi)

The cost of the laser depends on the gas engine for cogeneration, which varies widely, and it also depends on its usage, e.g., whether one laser is used per cylinder, or the pulses are delivered from one laser. The cost is expected to decrease from the current value of several million yen to several hundred or several tens of thousands of yen. Furthermore, the accumulation of soot or deposits on the laser window is another important issue. We have added a discussion about the cost and durability of the window.