Subtask 2.5A
COMBUSTION TECHNOLOGY REDUCING ENVIRONMENTAL IMPACT

Laser Ignition

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Subtask 2.5A

COMBUSTION TECHNOLOGY REDUCING ENVIRONMENTAL IMPACT

Member

- Dr. Akira. Miyoshi (University of Tokyo) (Group Leader)

“Kinetics and Mechanism of the Formation of Polycyclic Aromatic Hydrocarbon in Combustion with VUV-SPI-TOFMS”

(vacuum ultraviolet – single photon ionization – time of flight mass spectrometry).

> Important for formation and combustion of Soot

(PP38-41 of the outline and the activities of “THE COMMITTEE ON ACTIVE CONTROL OF COMBUSTION” IN JAPAN)

- Dr. Kentaro Tsuchiya (AIST)

“Theoretical Study about Low Temperature Oxidation of Dimethyl Ether”

> Important for analysis of reactions in HCCI

(PP88-94 of the outline and the activities of “THE COMMITTEE ON ACTIVE CONTROL OF COMBUSTION” IN JAPAN)

- Dr. Hirohide Furutani (AIST) > Laser ignition

Back ground

- Clean combustion and high thermal efficiency have been key words in combustion applications. To attain these targets, the lean combustion method has been researched and developed.
- In the recent years, the stratified-charge combustion techniques are used to burn lean mixtures. In these techniques, usually, comparatively richer mixture is carried to the ignition point near the engine wall by the intake-flow. However, these techniques pose a strict limitation on the selection of the ignition point.
- The laser ignition technique is expected as one of powerful methods to ignite such stratified-charge flow in the engines because it enables to make ignition at any point by taking the non-intrusive advantage.

Topics

- Single photon ignition

- Ignition with ArF Excimer laser
- Ignition of mixture added ozone with KrF Excimer laser

- Break-dowon

- （Gas-break-down）
- Target-break-down

Topics

- Single photon ignition

- Ignition with ArF Excimer laser
- Ignition of mixture added ozone with KrF Excimer laser

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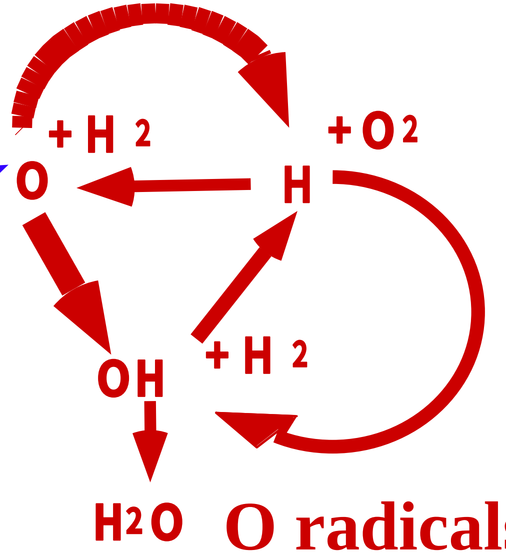
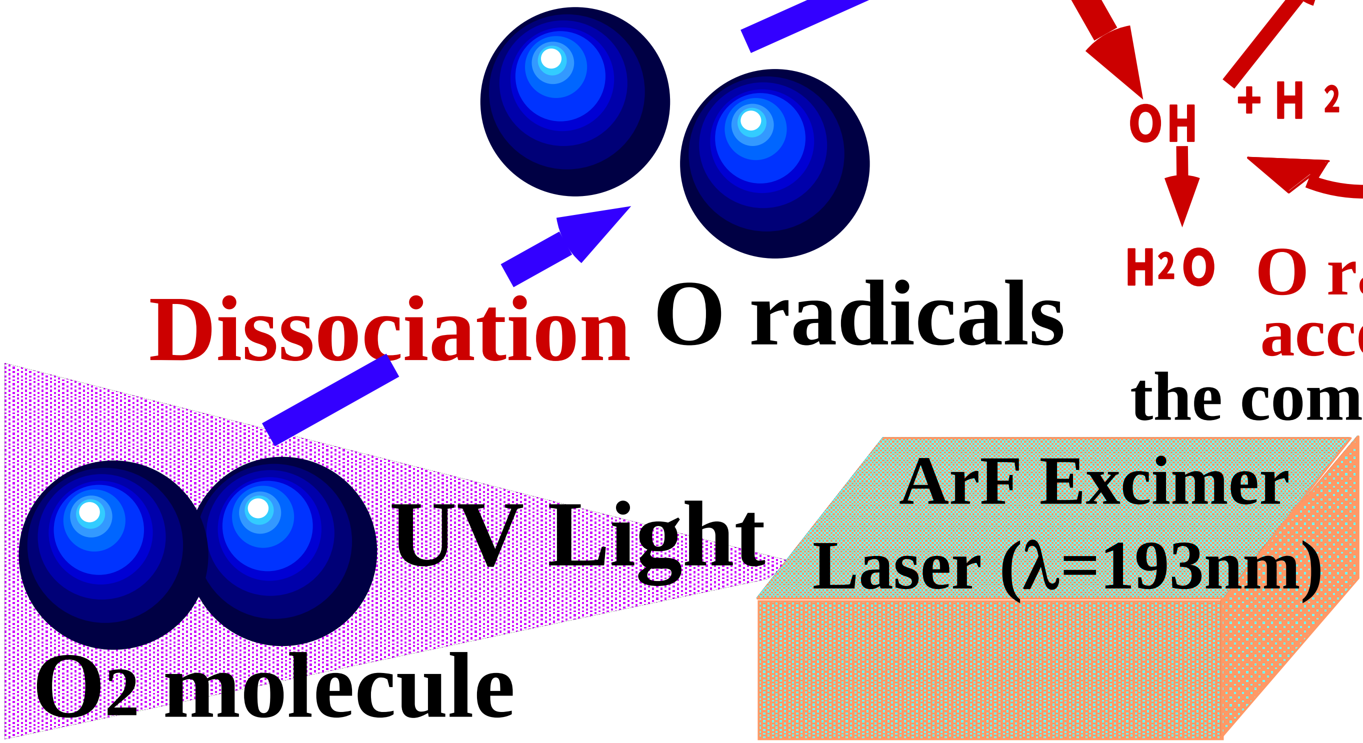
- (Gas-break-down)
- Target-break-down

Photochemical process : O_2 dissociation

Absorption band of O_2:
Schumann-Runge band
(175nm〜200nm)



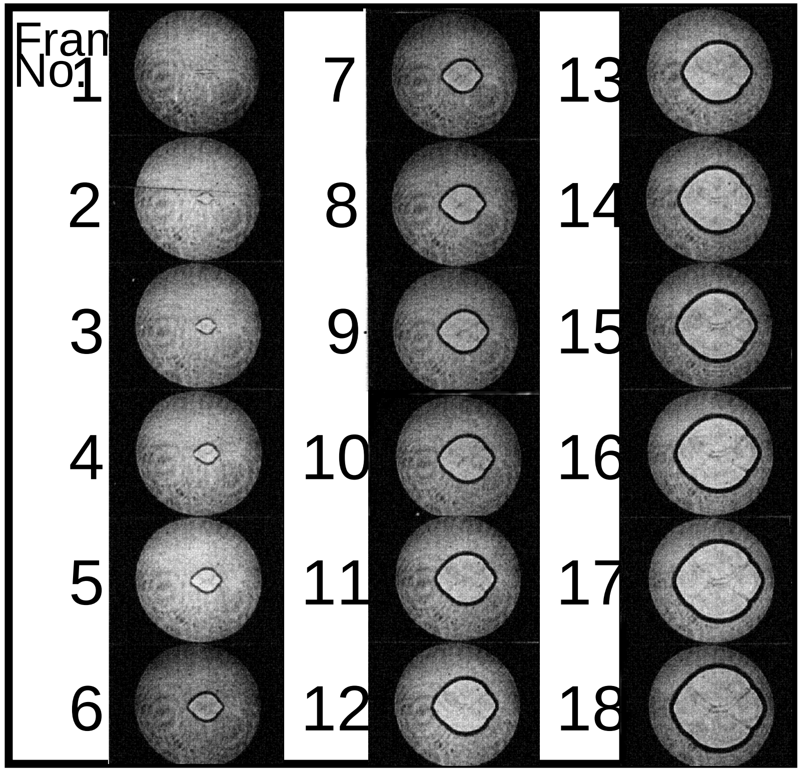
O radicals accelerate the combustion!



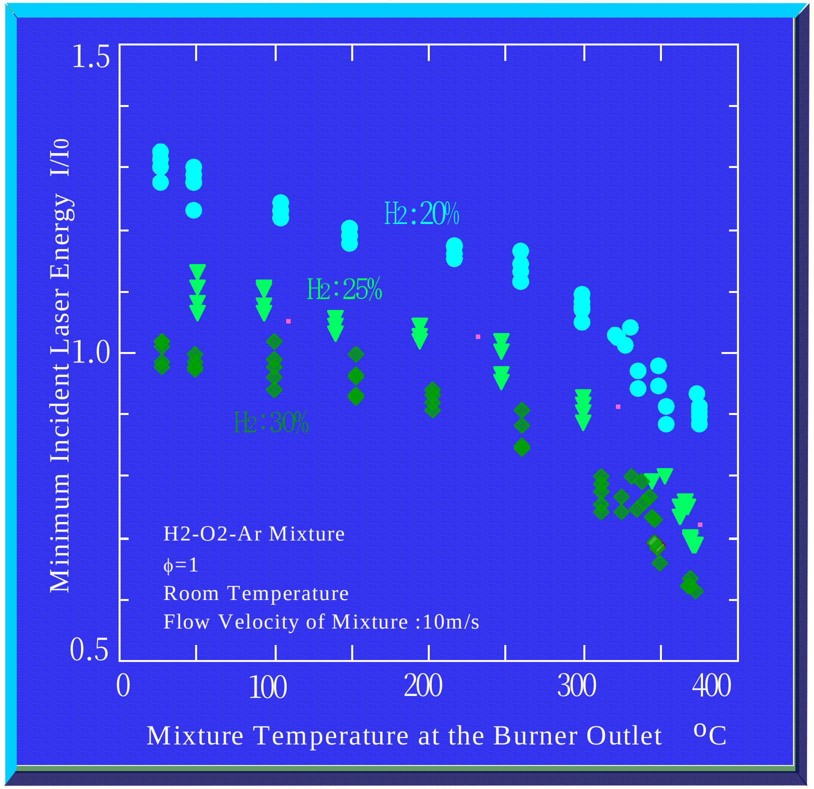
$O_2(X^3\Sigma u^-)+h\nu \rightarrow O_2(B^3\Sigma u^-)$

$O_2(B^3\Sigma u^-) \rightarrow \underline{2O(^3P)}$ + 122.3kJ/mol

Ignition with ArF Excimer Laser



Ignition process of mixtures with the ArF laser
H_2:20%,O_2:10%,Ar:70%(ϕ=1)
Initial gas pressure:0.08MPa
Frame speed: 10000f/s, Laser power: 286mJ



Dependence of Minimum Incident Laser Energy on Mixture Temperature

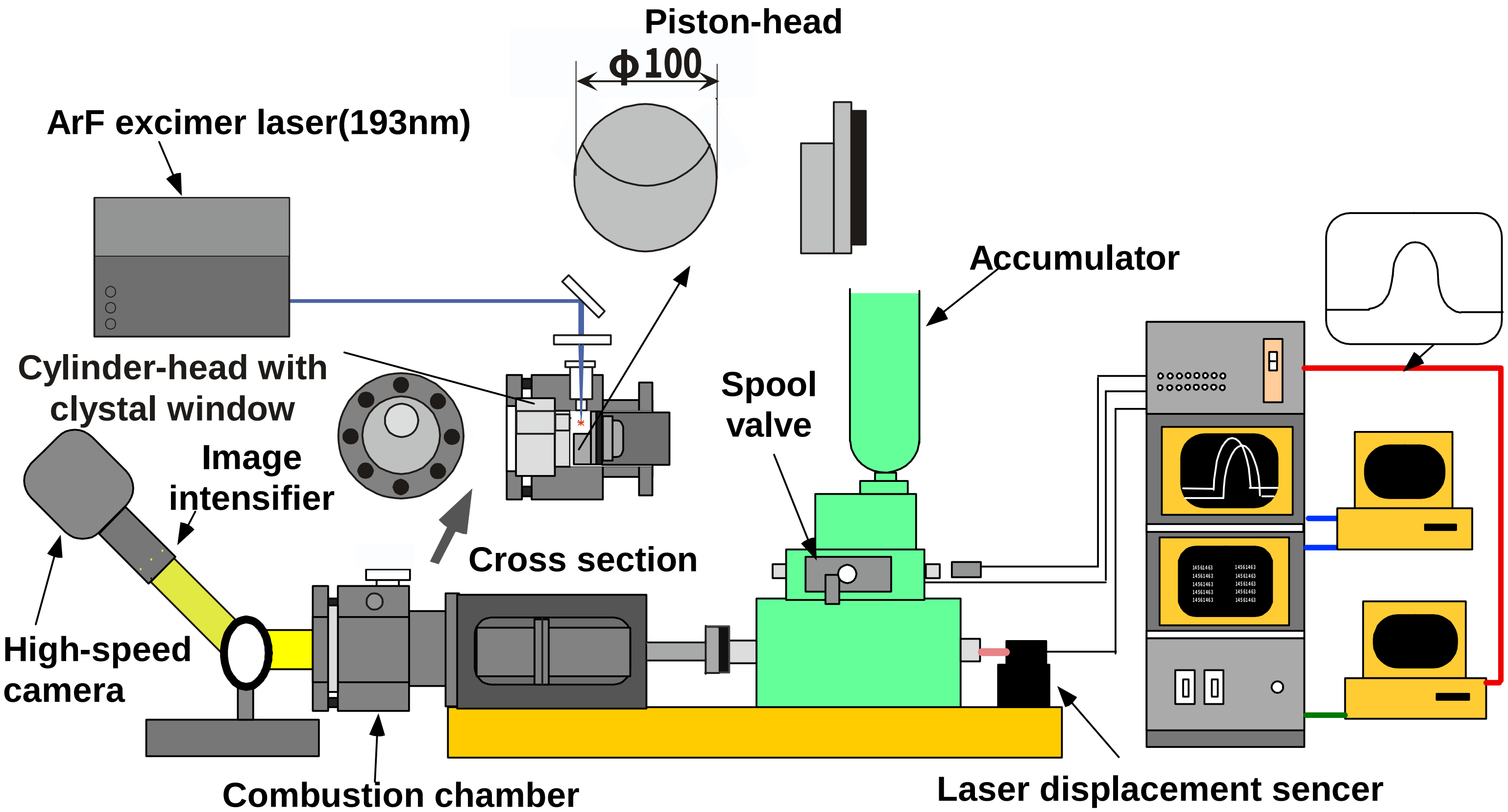
The ignition of rapid compressed mixture with ArF excimer laser

- The absorption coefficient of high temperature oxygen at the wavelength around the ArF excimer laser (193nm) is quite higher than room-temperature condition.

(like a rapid compressed mixture in the reciprocating engine.)

- We compress the pre-mixtures with the Rapid Compress and Expansion Machine and collect the laser light into the combustion chamber.

The ignition of rapid compressed mixture with ArF excimer laser – Experimental setup



The Rapid Compression and Expansion machine (RCEM) can simulate the single compression and expression strokes of a real reciprocating engine.

The ignition of rapid compressed H_2-O_2-Ar mixture with ArF excimer laser –Experimental condition

- mixture：H_2:16%、O_2:16%、Ar:68%
  (The mixture was mixed with mixing chamber for 1 hr)
- Laser:
  - Focusing lens：f=150mm
  - Laser was focused 32mm below from the window
  - Diameter of beam waist：0.15mm
  - Induced laser energy:4.0mJ (22.6J/cm^2 at the focus)
- Observation:
  - Shadow-graph method
  - Flame speed：10000f/s
  - Exposure time：40 μs

The ignition of rapid compressed H_2-O_2-Ar mixture with ArF excimer laser –ignition process

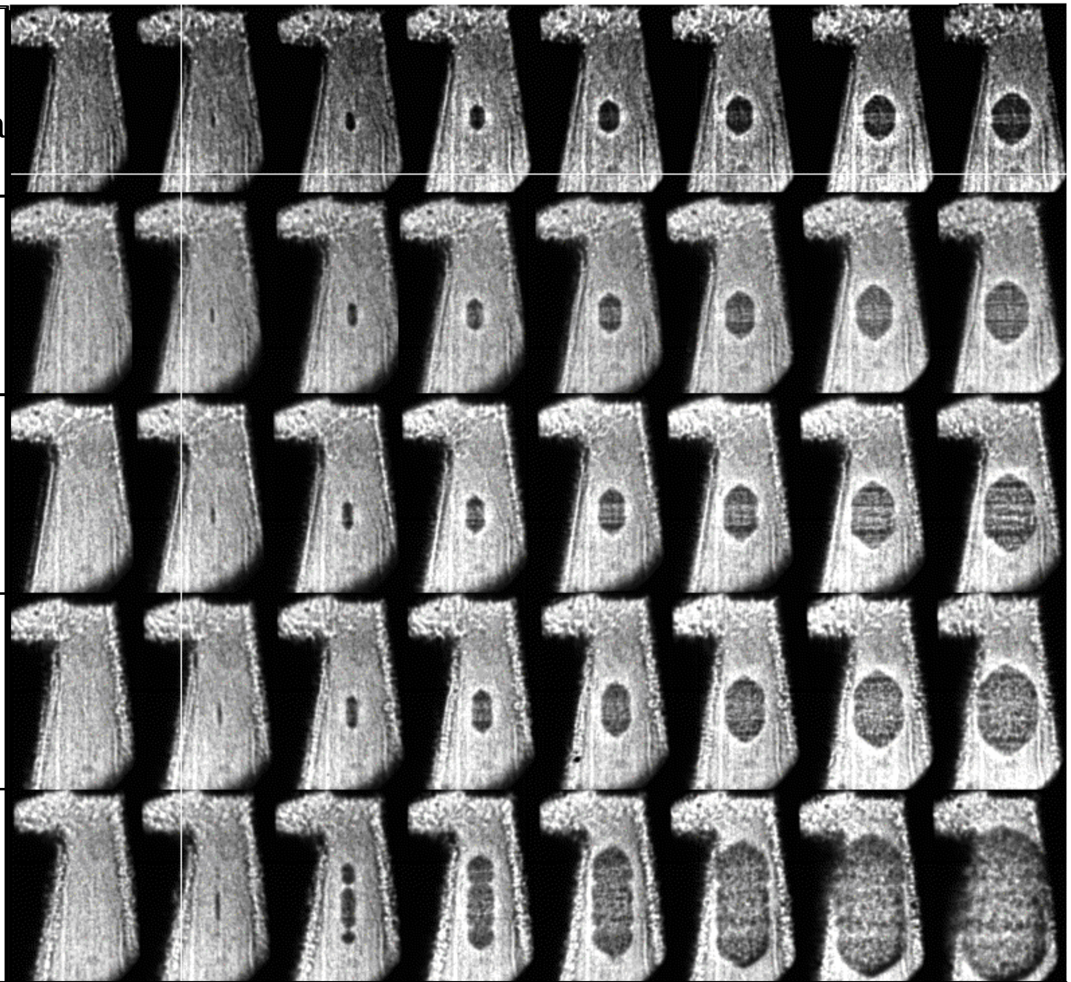
P_{ini}:0.06MPa
ε:2.72
P_{top}:0.31MPa
T_{top}:568K

: 0.06MPa
: 3.38
: 0.44MPa
: 648K

: 0.06MPa
: 3.38
: 0.44MPa
: 648K

: 0.06MPa
: 4.53
: 0.69MPa
: 763K

: 0.06MPa
: 5.95
: 1.04MPa
: 875K



-0.1ms | 0.0ms | 0.1ms | 0.2ms | 0.3ms | 0.4ms | 0.5ms | 0.6ms

Topics

- Single photon ignition

- Ignition with ArF Excimer laser

-Ignition of mixture added ozone
with KrF Excimer laser

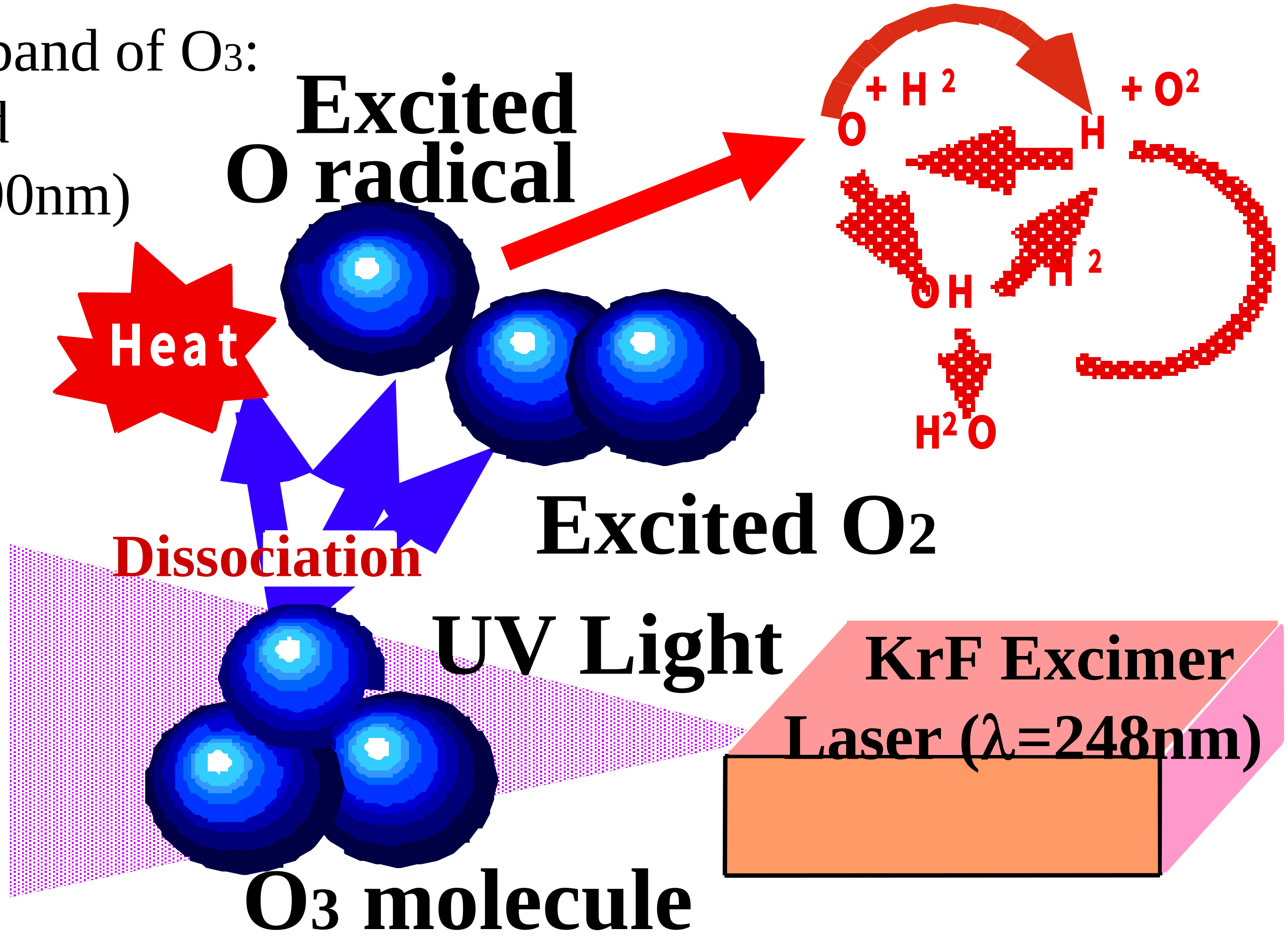
- Break-dowon

- Gas-break-down

- Target-break-down

Photochemical process : O_3 dissociation

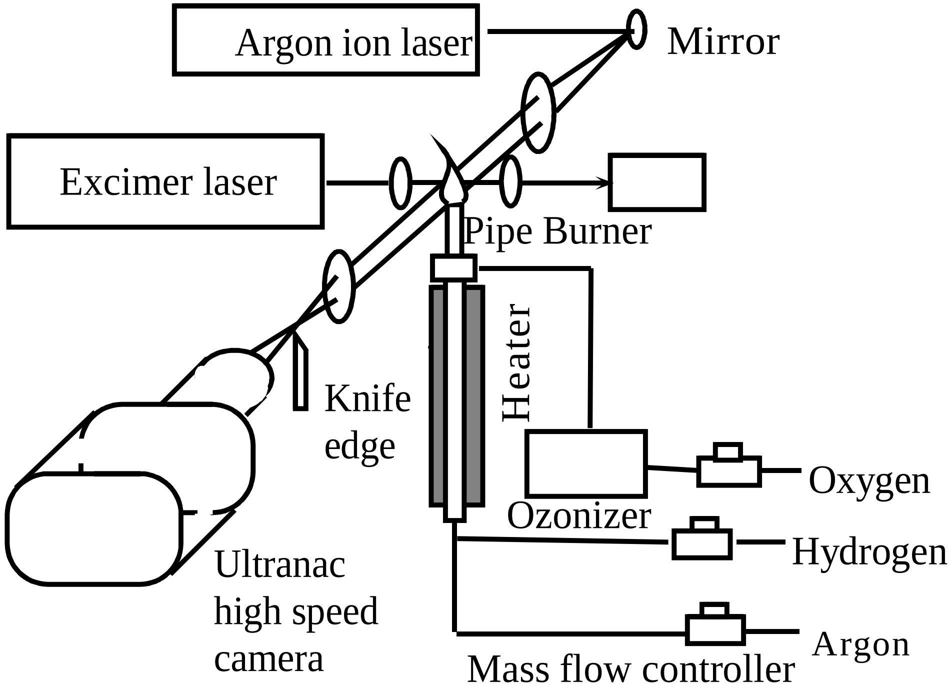
Absorption band of O_3:
Hartley band
(200nm〜300nm)



$$O_3(^1B_2)+h\nu \rightarrow O_3(^1A_1)$$

$$O_3(^1A_1) \rightarrow \underline{O(^1D)} + O_2(^1a\Delta_g) + 122.3\text{kJ/mol}$$

The ignition of H_2-O_2-O_3/H_2-O_2-O_3-Ar mixtures with KrF excimer laser



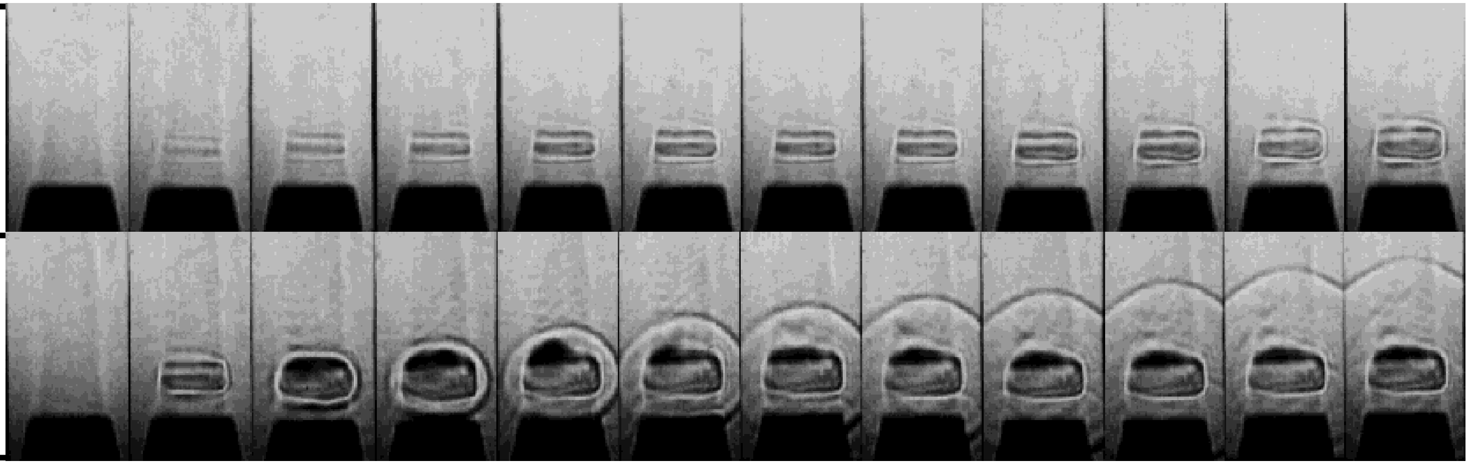
Schematic diagram of experimental apparatus

- We measured the Minimum Incident Laser Energy needed to ignition (MILE) of H_2-O_2-O_3/H_2-O_2-O_3-Ar mixtures with KrF excimer laser .

The ignition of H_2-O_2-O_3/H_2-O_2-O_3-Ar mixtures with KrF excimer laser – Observation of ignition process

5,000,000f/s
O_3:0.6%
Lp = 315mJ
Room temp.

500,000f/s
O_3:0.6%
Lp = 273mJ
Room temp.



Ignition process of H_2-O_2-O_3 mixture induced by KrF laser (ϕ=1.0)

- The ignition process was extremely faster.
- The shock-wave was observed immediately after laser induced.

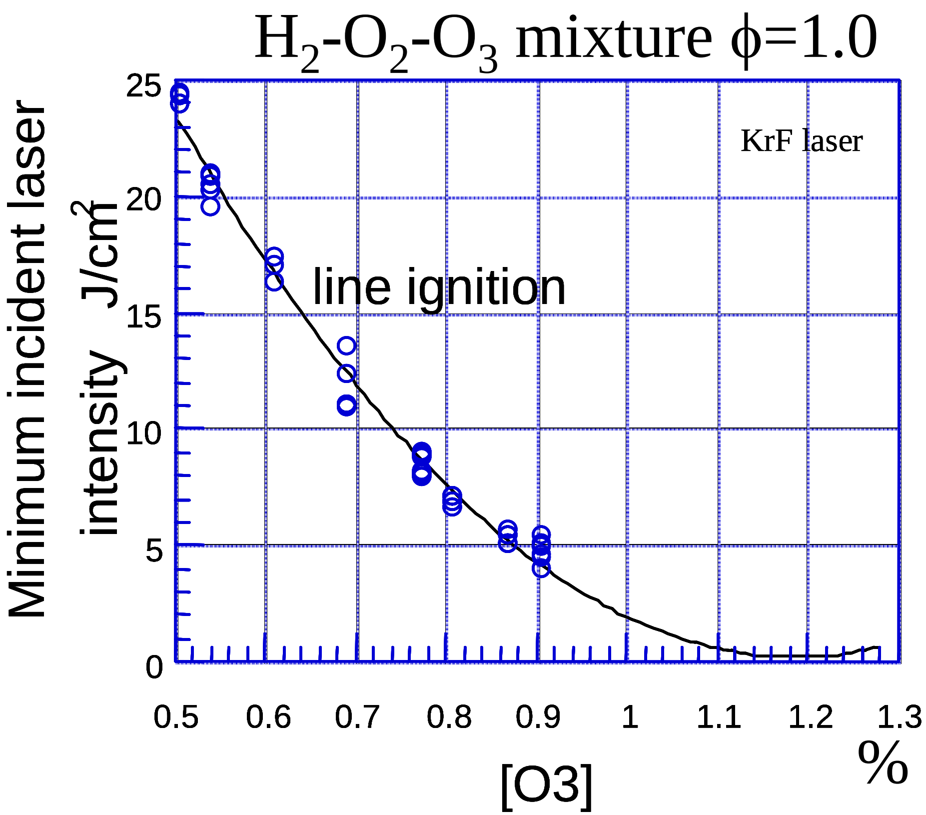
(**The shock-wave was caused by not only the heat release from photolysis of ozone, but also the heat release from the reaction between hydrogen and the O(1D) or follow-up reactions, because the significant shock wave was not observed in the O2-O3.**)

Photochemical process : Comparison

Laser	ArF	KrF
Wavelength	193nm	248nm
Absorber	O_2	O_3
Photolysis(10)	O_2+hν--2O(^{3}P)	O_3+hν--O(^{1}D)+O_2($^1\Delta$)
Chain branching Reaction rate constant	O(^{3}P)+H_2--OH+H -ΔH ΔH=8.26kJ/mol τ=7.5ms* 347--742K A=8.8×10^{-12} k=Aexp(-4200/T) cm^3/molecule/s	O(^{1}D)+H_2--OH+H-ΔH ΔH=181.9 kJ/mol τ=0.5ns* 200--350K A=1.1×10^{-10} k=A cm^3/molecule/s

$$*\tau = \frac{[O]}{k[O][H_2]} = \frac{1}{k[H_2]},$$

The ignition of H_2-O_2-O_3/H_2-O_2-O_3-Ar mixtures with KrF excimer laser – Measurement of (MILE)



Relationship between MILEI and ozone concentration

When the concentration of O_3 was over 0.5%, the Minimum Incident Laser Energy (MILE) needed to ignition was decreased with the concentration of O_3.
It shows the hard relationship of the ignition process and the absorption of O_3.
At the same time, it suggests that the photolysis caused the ignition.
Because if the ignition caused by breakdown then it should show the more hard dependency on MILE needed to ignition.
We predicted that if we increase the concentration of O_3 and use a high power laser, we can ignite wide area.

Topics

- Single photon ignition

- Ignition with ArF Excimer laser
- Ignition of mixture added ozone with KrF Excimer laser

- Break-dowon

- （Gas-break-down）
- Target-break-down

The ignition with target-break-down
-merit of target-break down -

1)The minimum laser power to induce the break-down with target is much smaller than gas-break-down.

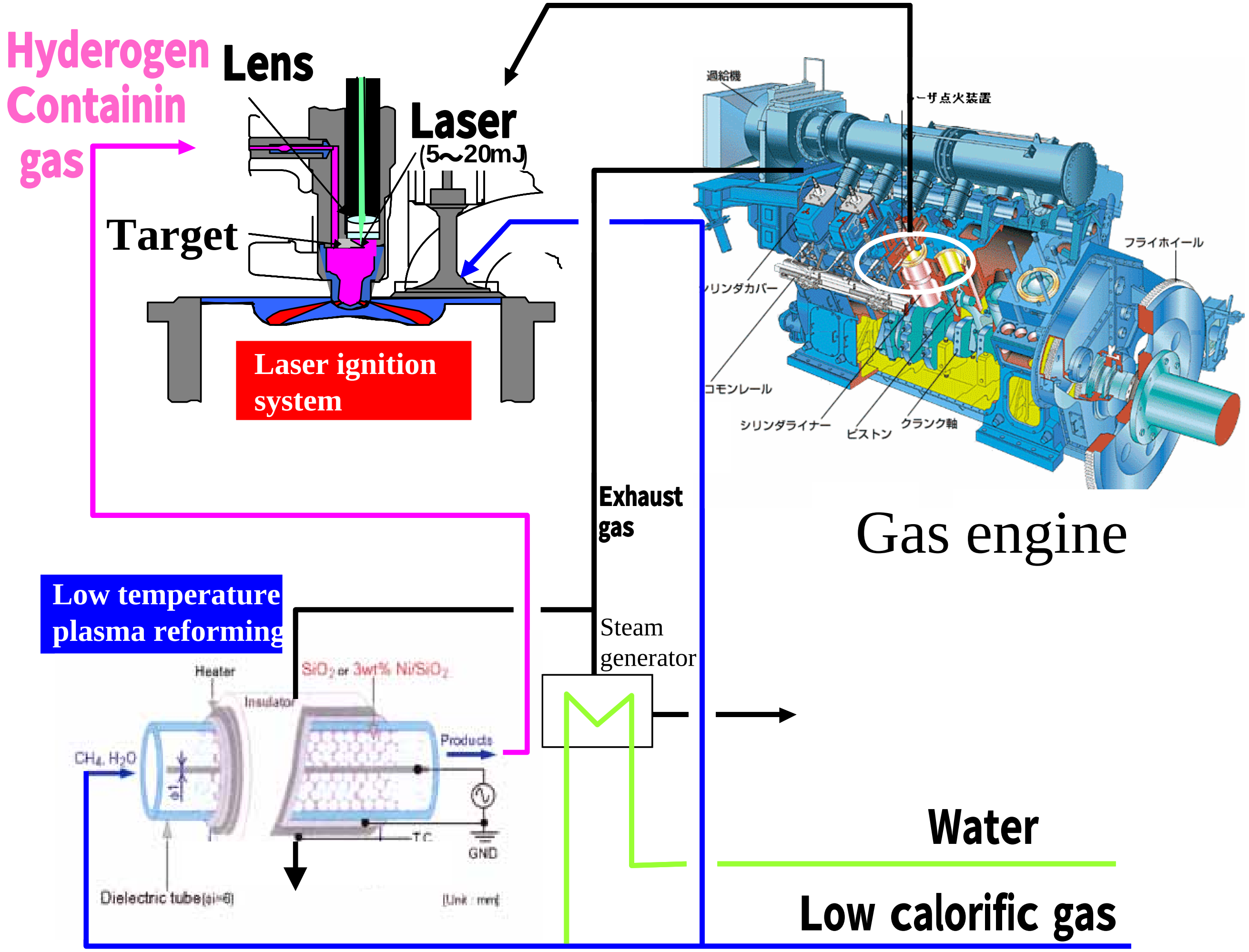
2)The needed quality of laser light to induce the break-down at the target is not so high compared with gas-break-down.

>>It is expected that we can use an optical fiber to transmit the laser light to ignite.

It is a big merit for engine systems and laser systems too.

Development of a clean and energy-saving engine utilizing hydrogen-containing flames by low-temperature plasma reforming and ignition with target-break-down was done in the project.

The ignition with target-break down
- Gas engine system for ultra lean fuels-



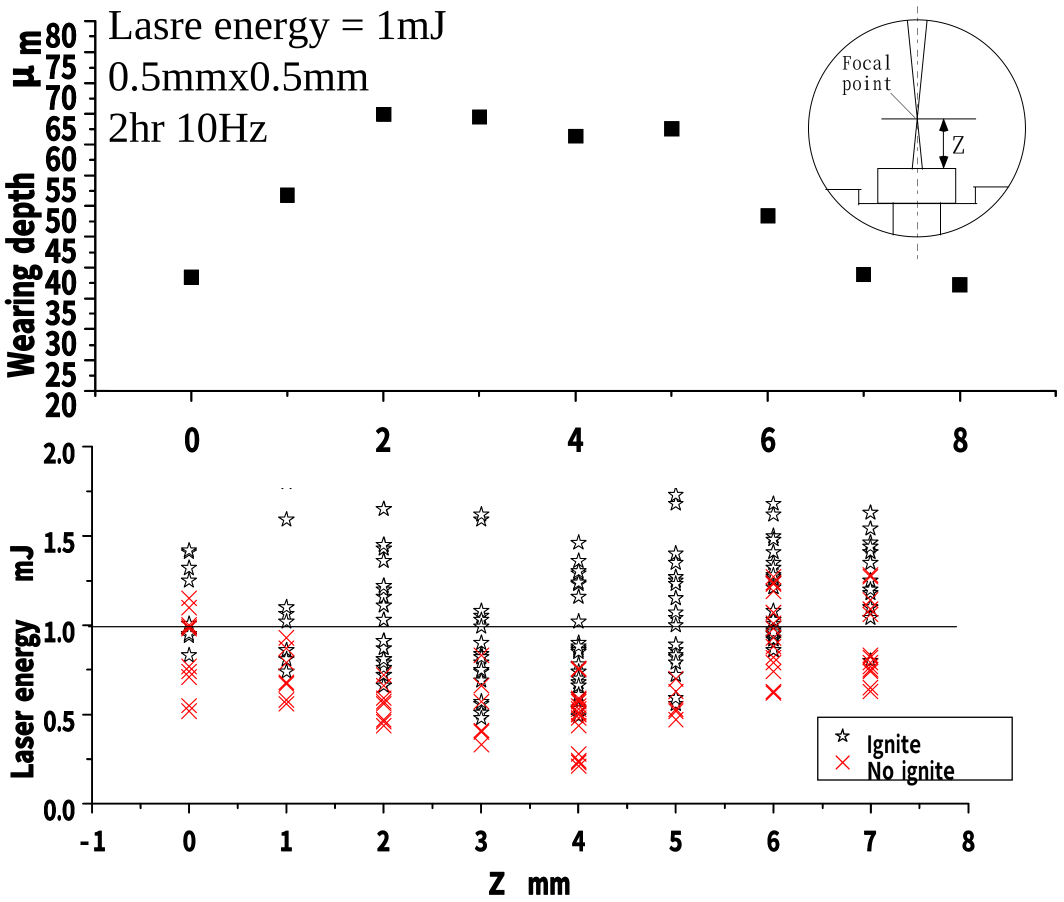
In order to promote combustibility of ultra lean fuels such as low-calorific biogas in an internal combustion engine, a part of feed fuel was reformed in advance to enriched hydrogen.

Such reformed fuel is readily ignited in an auxiliary chamber of the engine with the help of laser ignition system, enabling high-efficient operation of internal combustion engine with low-calorific fuels.

We built-up and demonstrated power generation facility based on commercial gas-engine system equipped with plasma/catalyst hybrid reactor for low-temperature fuel reforming and laser ignition system.

(This work was done with MHI, Nippon Steel and Tokyo Institute of Technology and it was supported by NEDO)

The ignition with target-break down
-Wearing of target and minimum laser energy to ignite -

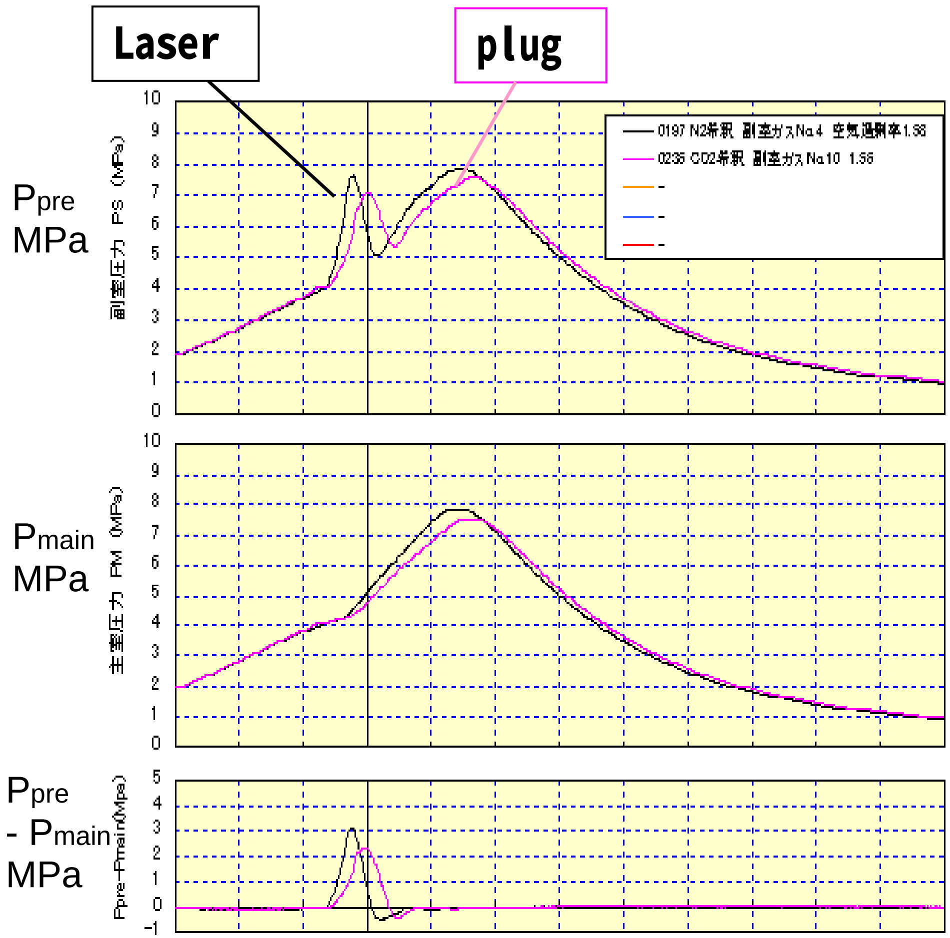


MILE<1mJ z=1~5 > life-time of target <100,000hr
> optical fibers was available

The fundamental experiments with RCEM (Rapid compression and expansion machine) clarified the influence of the fuel dilution and reforming into hydrogen on the minimum laser power to ignite.

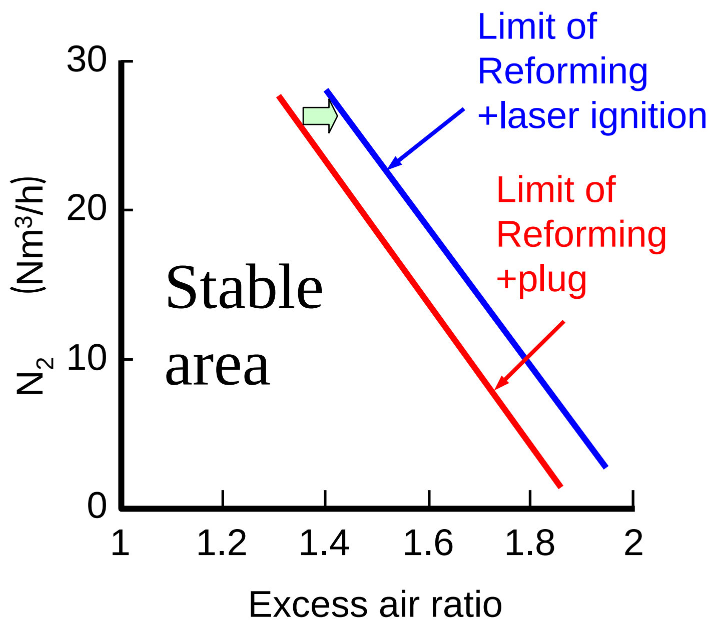
And, the wearing depth of target was measured under several conditions. The results predict that the durability will be over 10,000 hours under minimum ignition condition.

The ignition with target-break down
-result of engine test-

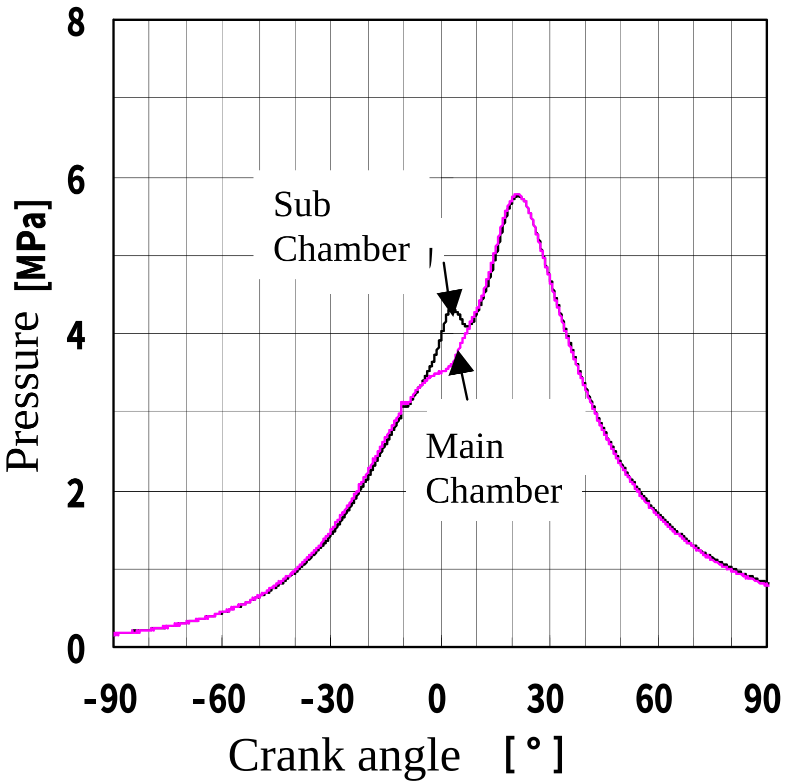


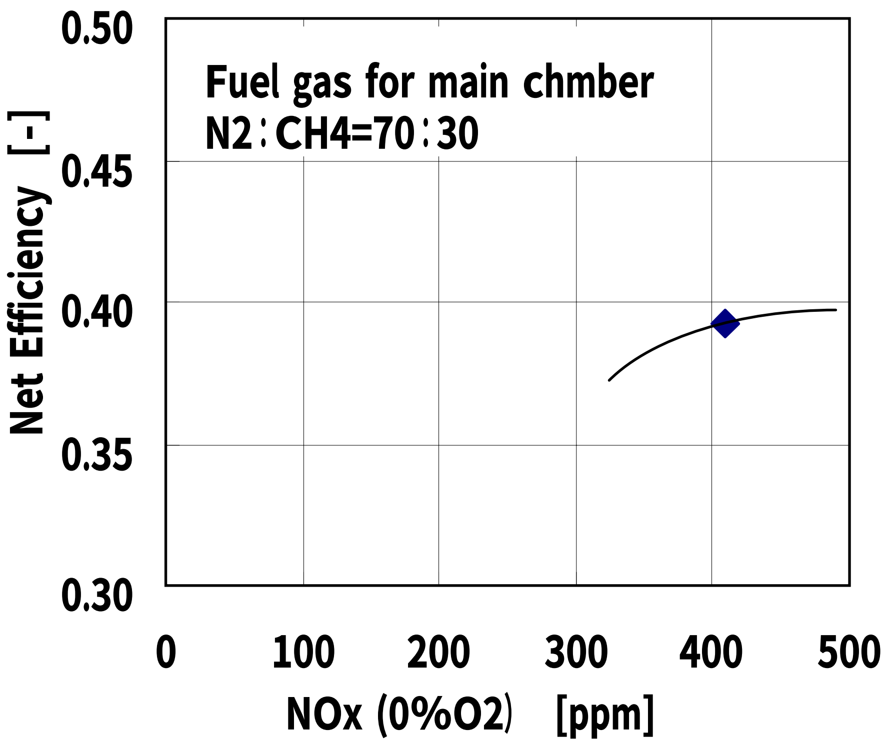
Condition：Fuel:CH_4=100%

CH_4	7.1Nm³/h
Ignition timing	−9.5ATDC
Laser energy	1mJ



The ignition with target-break down -result of engine test-





It was confirmed by the increase of conversion ratio from methane to hydrogen for pre-combustion chamber fuel that the misfire limitation for low-grade fuel was enlarged. Finally in the total system verification tests the engine performance was evaluated when fuel methane was diluted in large quantity (CH4:30%,N2:70%). The output power is about 200kW. It was found that the thermal efficiency was 39.3 %.

Summary single photon ignition

Ignition with ArF Excimer Laer

In H_2-O_2-Ar mixtures, minimum incident laser energy to ignite (MILE) was decreased over 523K(250℃).

In the H_2-O_2-Ar mixtures compressed rapidly, ignition was occurred with laser power of 4mJ. The length of ignition point was drastically increased over 700K.

Ignition of H_2-O_2-O_3mixture with KrF Excimer Laser

The ignition was occurred instantly after irradiation of laser, the shock waves were observed with ignition. It is considered that this sudden ignition was induced by the reaction of $O(^1D)$ with H_2. Increasing of O_3 concentration made the MILE decreased drastically.

Summary of ignition with target-break-dowm

When the break-down was occurred with target, the MILE was decreased compared with gas-brake-down and the using of fibers as a transfer system of laser was available.
From the measuring of the wearing depth and MILE in engine conditions , the life time of target was expected over 100,000hr.

It was confirmed by the misfire limitation for low-grade fuel was enlarged with target-break-down in our experimental condition.

In the total system verification tests, the engine performance was evaluated when fuel methane was diluted in large quantity (CH_4:30%, N2:70%). The output power is about 200kW. It was found that the thermal efficiency was reached to 39.3 %.

Subtask 2.5A
COMBUSTION TECHNOLOGY REDUCING ENVIRONMENTAL IMPACT

Ignition with laser

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***2 Meisei Univ.**

ABSTRACT

The laser ignition is expected as a new technique to control the ignition of future engines. In AIST (Advanced industrial science and Technology), the laser ignition technique has been researched for 15 years. This paper shows some topics from these works. At first, one-photon ignition with UV-laser is introduced. In this technique, ignition was occurred with photochemical reactions induced by UV-light, then the effect was acted into whole part which is irradiated with UV-light and bulk ignition was controlled. Next, the ignition technique with laser break-down is introduced. With this technique, it was reported that lean limit of gas engine was wider and low calorific gases (bio-gas, land-fill-gas and CBM etc.) were expected to be used by gas engine efficiently. Here we show the results of the project to use a low-calorific gas with gas engine efficiently with laser ignition and reforming with low temperature plasma.

INTRODUCTION

The objective of this subtask is to obtain combustion technology for reducing environment impact. Until now, NOx, SOx, THC, CO and Soot have been noticed as products from combustion which impact environment. For these products, the regulations have been strictly and strictly and the exhaust gases under these regulations have been cleaner and cleaner by each regulation. In Japan, the new regulation is going to be introduced in 2009. It is considered that the vehicles with heavy duty diesel engines will need DPF (Diesel Particulate Filter) to fit these regulations. Many people are interesting in the combustion phenomena in the DPF. A reader of our subtask, Dr. A Miyoshi is studying "Kinetics and Mechanism of the Formation of Polycyclic Aromatic Hydrocarbon in Combustion" with VUV-SPI-TOFMS(vacuum ultraviolet – single photon ionization – time of flight mass spectrometry). These kinetics and mechanism are quite important to clear the process of soot formation from combustion and to predict the combustion process of soot in DPF.
(For detail, please refer PP38-41 of the outline and the activities of "THE COMMITTEE ON ACTIVE CONTROL OF COMBUSTION" IN JAPAN.)

On the other hand, emission of GHG (Greenhouse Gas) is considered as a source of a big environmental impact. To reduce the emission of CO_2, improvement of efficiency in each process is important. To attain these targets, the lean combustion method has been researched and developed. The stratified-charge combustion techniques are used to burn lean mixtures. In these techniques, usually, comparatively richer mixture is carried to the ignition point near the engine wall by the intake-flow. However, these techniques are strictly limited by the selection of the ignition point. The laser ignition technique is expected as one of powerful methods to ignite such stratified-charge mixture in the engines because it enables to make ignition at any point by taking the non-intrusive advantage. The laser ignition techniques have been studied many researchers[1-9]. As a basic study to improve the efficiency of energy conversion system, the research of laser ignition was started in AIST[10-14]. On the other hand, for some kind of GHG (methane included in the landfill gas, bio gas, CBM and etc.), we can use combustion not only to reduce the emission them but also to use them effectively. In these applications, it is expected that laser ignition techniques extend the lean and diluted limit to use for gas-engine.

SINGLE PHOTONE IGNITION METHOD

- Ignition with ArF Excimer laser –

Figure 1 shows the concept of photochemical ignition with ArF excimer laser. The wave length of ArF excimer laser is 193 nm near the edge of the O_2 Shumann-Runge band. Hoever the absorption is weak, the photon energy is enough to dissociate oxygen molecule into oxygen radical and the oxygen radical accelerate the ignition process.

At first, we carried out experiments on ignition for hydrogen-oxygen-argon mixtures by use of ArF excimer laser. The phenomena of the ignition and the flame growth were observed by using a high speed camera and a shadowgraphy method. We also evaluated the minimum incident laser energy needed to ignite mixtures under various oxygen concentrations and the initial pressure of mixtures.

Figure 2 shows typical shadowgraphs for the ignition and flame propagation. In this case, the mixture had the concentration of 20% H_2, 10% O_2, and 70% Ar and initial gas pressure of 0.08 MPa. Incident laser energy was 286 mJ and the optical path of the excimer laser was filled with N_2. The camera frame speed was 10000 frame/sec. The laser beam came from the left side of each photo frame and went through to the right of the pictures.

A series of photographs indicate that two straight streaks appeared firstly in the focal region of the laser immediately after the laser irradiation, and in the same first frame. The flame kernel occurred suddenly at the two streaks. After that, the flame kernel grew, keeping an elliptical shape with projections in the direction of laser optical axis, which looked like a lemon. The projection in the laser incident side was bigger than in the other side. The propagating speed in the direction of laser axis was larger than in the perpendicular direction. Then the difference of the propagating speeds in both directions generated the discrete line on the elliptical flame. This flame kernel did not have characteristic shape which ignited by laser break-down.

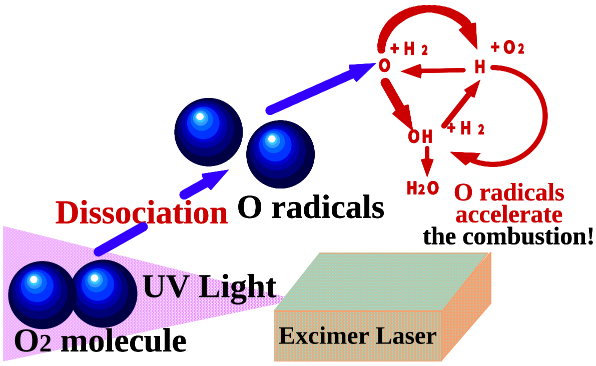
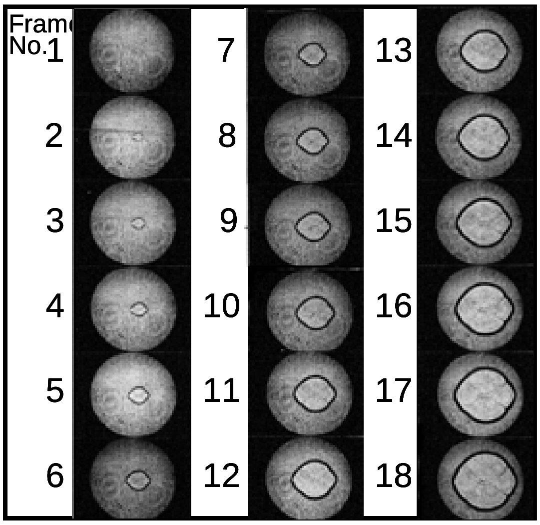


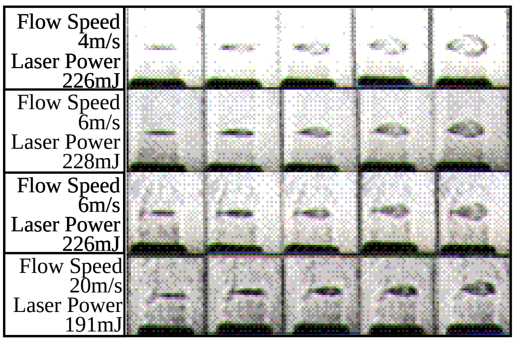
Fig.1 Photochemical ignition process



H2:20%, O2:10%, Ar:70% (ϕ=1.0) Initial gas pressure:0.08MPa
Frame speed:10000 f/s Laser power 286mJ

Fig.2 Ignition process of mixtures with the ArF laser

Figure 3 shows the ignition and flame kernel growth of mixture flow. Ignition processes were almost similar and independent on the flow speed, but, the subsequent flame propagation processes depended on the flow speed. The excimer laser was able to induce chemical reactions in the emission time of 10ns and the ignition process was so quick that the ignition delay was much shorter than the characteristic time of mixture flow.Figure 4 shows the influence of the pre-heat temperature into the minimum incident laser energy for ignition. Minimum incident laser energy decreased drastically above 250℃ irrespective of hydrogen concentration. Under the condition of the actual system with higher temperature, we can expect that the Minimum incident laser energy decrease to the practical level.



(H2:30,O2:15%,Ar:55%, Frame Speed 100,000F/s)

Fig.3 Ignition and flame kernel growth of mixture flow

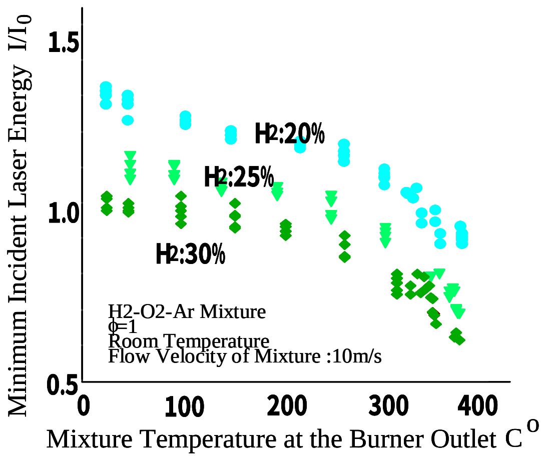


Fig.4 influence of the pre-heat temperature with minimum incident laser energy for ignition

The absorption coefficient of high temperature oxygen at the wavelength around the ArF excimer laser (wavelength 193nm) is quite higher than room-temperature condition like a rapid compressed mixture in the reciprocating engine. We compress the pre-mixtures with the Rapid Compress and Expansion Machine (RCEM) and focused the laser light into the combustion chamber. The RCEM can simulate the single compression and expression strokes of a reciprocating engine. Figure 5 shows the influence of temperature into the ignition process of rapid compressed H_2-O_2-Ar mixture (H_2:16%,O_2:16%,Ar:68%). The frame speed is 10000f/s. We got a simultaneously line ignition with comparatively low laser energy (4mJ) in high temperature conditions. This ignition implies the possibility of controlling the bulk ignition with UV light. The area ignited simultaneously was expanded with the temperature.

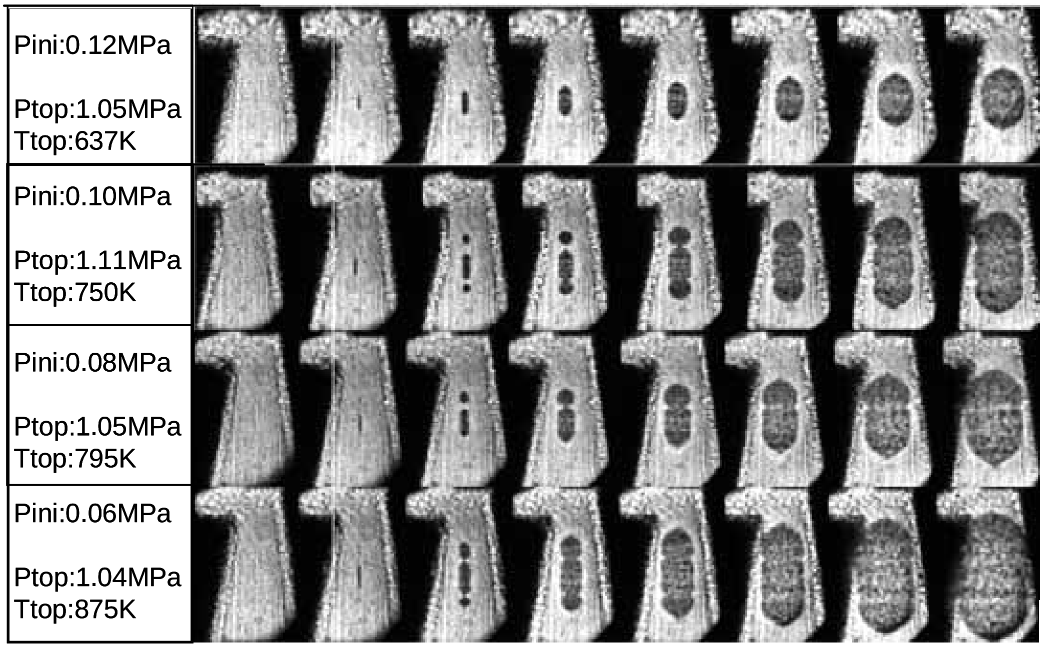


Fig.5 Influence of temperature into ignition process

To reveal the adaptability of this method for Hydro-carbon fuel, we made a experiment about the laser induced ignition of rapid compressed CH4-air mixture with ArF excimer laser, and observed the OH* emission at the ignition process. Figure 6 shows the ignition process of rapid compressed CH4-air mixture with ArF excimer laser. When the laser was irradiated into the chamber, the OH* intensity was strong along a line intersecting the focal point. This indicates that the O radials, which were disassociated from O_2 by laser irradiation, consumed CH_4 and generated OH*. Subsequently, OH* intensity weakened initially, and then strengthened when the flame propagation was observed 0.6 ms after TDC. Therefore, the luminescence became stronger and larger with time. These results suggest that it is possible to ignite a large volume.

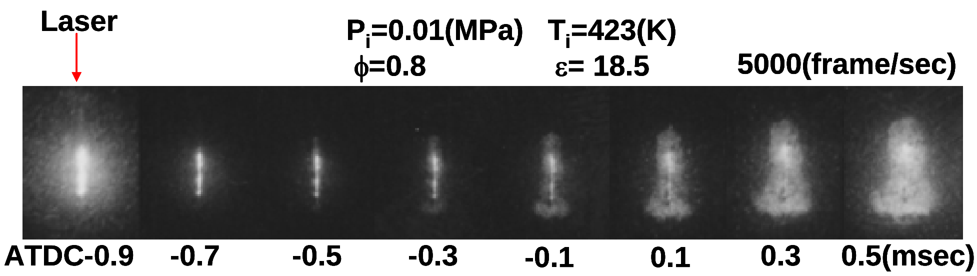


Fig.6 Ignition process of rapid compressed CH4-air mixture with ArF excimer laser

- Ignition of mixture added ozone with KrF Excimer laser –

We took noticed of ozone as a strong absorber for KrF excimer laser(wavelength =248nm), because the peak absorption of ozone in the Hartley bands is near 250nm, and it's absorption coefficient is 130$cm^{-1}atm^{-1}$. Furthermore, the photolysis products of ozone with irradiation from KrF laser are O(1D) and O2(1D), more actively than ground state O(3P) induced by photolysis of oxygen.

Figure 7 shows the ignition process of H_2-O_2-O_3 mixture induced by KrF laser. The ignition process was extremely faster and a shock-wave was observed immediately after laser induced. The shock-wave was caused by not only the heat release from photolysis of ozone, but also the heat release from the reaction between hydrogen and the O(1D) or follow-up reactions, because the significant shock wave was not observed in the O_2-O_3.

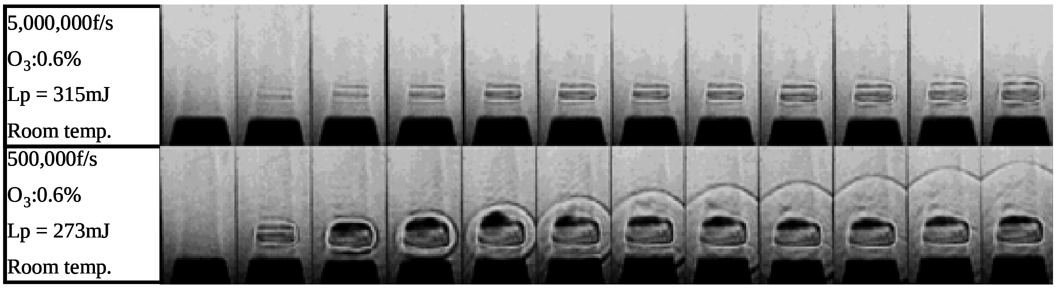


Fig.7 the ignition process of H_2-O_2-O_3 mixture induced by KrF laser

Figure 8 shows the influence of O_3 concentration upon incident laser intensity to ignite. When the O_3 concentration was under 0.5%, the KrF laser did not induce ignition even with the maximum power of 650 mJ on the room temperature condition. Although, when the concentration of O_3 was over 0.5%, the Minimum Incident Laser Energy needed to ignition was decreased with the concentration of O_3. It shows the hard relationship of the ignition process and the absorption of O_3. At the same time, it suggests that the photolysis caused the ignition. Because if the ignition caused by formation of plasma like a breakdown then it should show the more hard dependency on Minimum Incident Laser Energy needed to ignition. We predicted that if we increase the concentration of O_3 and use a high power laser, we can ignite wide area. Under the results of the ignition of H_2-O_2-O_3 mixture with KrF laser using the spherically lens, it expected the simultaneous ignition of whole mixture radiated by the laser light. We had experiment of the flat ignition by using the KrF laser sheet. Fig. 9 shows the process of the flat ignition. First, the edge of the mixture flow was emphasized. Next, the center part of mixture was ignited simultaneously. After that, the flame area was extended quickly. As the observation, the ignition delay was longer and the initial ignition kernel area was smaller with the decrease of incident laser energy. But the growth speed was almost same and the speed was over 3km/s. The usual flame speed, it would be called simultaneous bulk ignition compared with usual flame speed.

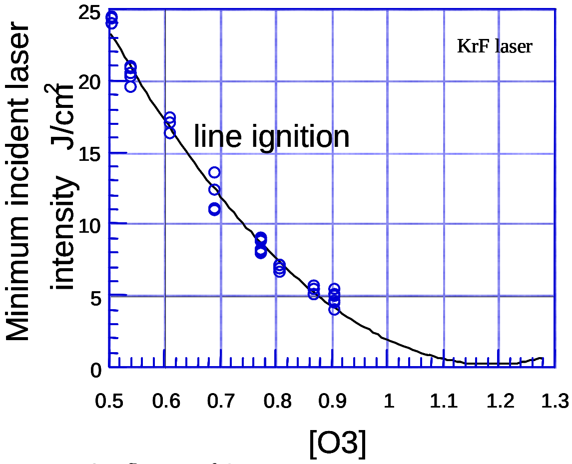


Fig.8 Influence of O_3 concentration upon incident laser intensity to ignite

Fig.9 Ignition process of plane ignition on each ILE condition
(H2:66.7%, f=1.0, Flow speed of mixture: 2.1m/s, Frame speed:5,000,000f/s)

BREAK-DOWN METHOD

The Nd:YAG lasers excited with semiconductor light source were developed and these are smaller and durable compared with the gaseous-laser. Therefore, there is possibility to be the light source for ignition of engine system earlier than UV-laser. When we use Nd:YAG laser for ignition, the ignition was occurred with break-down at the focus point. Specifically, for the gas engine which needs supercharging, the research of laser ignition is developed as one of the steady ignition ways at the high pressure. In Europe, the TU Wien and Jenbacher are developing these techniques[6,7]. In U.S., a consortium was formed in the industry-university-government to develop them[8,9]. Small laser ignition equipment is developed in AVL in recent years and the attention becomes higher suddenly.

AIST is studying the ignition method using a break-down with Nd:YAG laser too. In this method, two ways are considered. One is a way using gas-break down and the other one is way using target-break-down. When we use a gas-break-down, we can choose any ignition point in combustion chamber and we do not need target, but comparably higher laser power is needed. When we use a target-break-down, break-down is occurred with lower laser power compared with gas-break-down.

- Ignition with gas-break-down –

Figure 10 shows the flame kernel ignited with gas-break-down. The shape is like a couple of doughnuts. This is distinctive shape of the flame kernel induced gas-break-down ignition. The cause of twin vortex-rings is considered to be a strong stretch flow induced by break-down. This shape is different from the flame kernel ignited with ArF excimer laser. Figure 11 shows the influence of in-cylinder pressure into the minimum peak power to ignition. The minimum peak power to ignition was decreased with in-cylinder pressure (Fig. 11). This character is a big merit when laser ignition is applied to engines, because the needed voltage to occur a break-down is increase with pressure by using usual plug. Especially, for gas-engines, the pressure conditions at ignition are quite high and laser ignition is expected to expand the limit of supercharging.

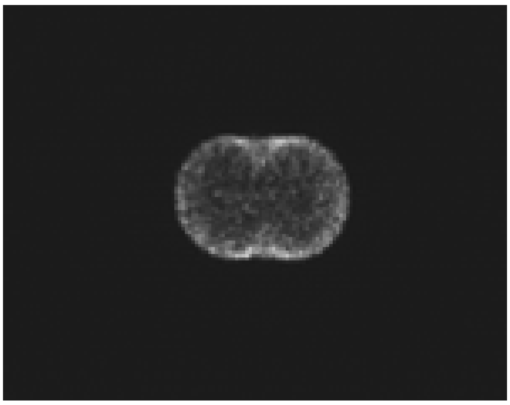


Fig.10 flame kernel ignited with gas-break-down
CH4-Air(Φ=1.0)、0.1MPa、300K

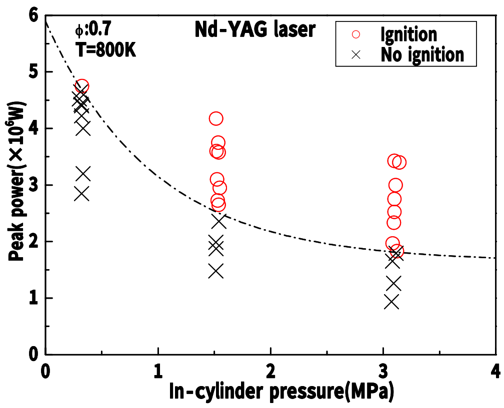


Fig.11 Influence of pressure
into the minimum peak power of laser to ignite

One of the important merits of laser ignition is that we can choose any point to ignite. And it makes multi point ignition easy. Figure 12 shows the combustion processes when we ignite the mixture in combustion chamber. “Wall” shows that the ignition point is at the side wall of the chamber and “SS” shows it is at the center of the chamber. In “3S” and “3L” the ignition points are three. In “3S” the distance between each ignition point is short (10mm) and in “3L” it is long (17.3mm). Figure 13 shows the heat release rate of each case. The heat release rate of “Wall” was smaller and had a flat top. It is considered that the flame propagation was limited by the wall of combustion chamber. In the other case the heat release rate had a peak and they were bigger. “3L” is fastest and “3S” is faster than “SS” at the just after ignition. The tops of each case were almost same.

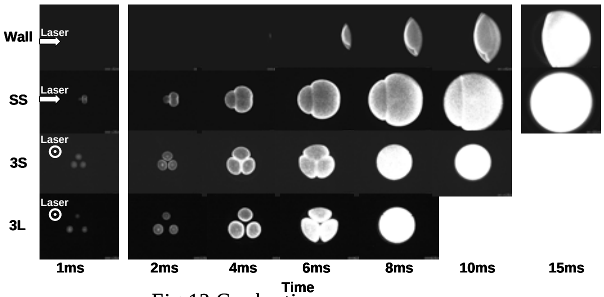


Fig.12 Combustion processes

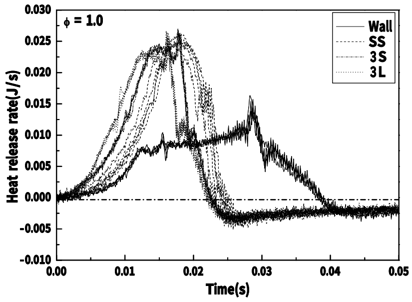


Fig.13 Heat release rate

- **Ignition with target-break-down –**

The minimum laser power to induce the break-down with target is much smaller than gas-break-down. And the needed quality of laser light to induce the break-down at the target is not so high compared with gas-break-down. It is expected that we can use an optical fiber to transmit the laser light to ignite. It is a big merit for engine systems and laser systems too.

Development of a clean and energy-saving engine utilizing hydrogen-containing flames by low-temperature plasma reforming and laser ignition. In order to promote combustibility of ultra lean fuels such as low-calorific biogas in an internal combustion engine, a part of feed fuel was reformed in advance to enriched hydrogen. Such reformed fuel is readily ignited in an auxiliary chamber of the engine with the help of laser ignition system, enabling high-efficient operation of internal combustion engine with low-calorific fuels. Ignition capability of reformed fuels is tuned by either hydrogen content or laser power. We built-up and demonstrated power generation facility based on commercial gas-engine system equipped with plasma/catalyst hybrid reactor for low-temperature fuel reforming and laser ignition system. (This work was done with MHI, Nippon Steel and Tokyo Institute of Technology and it was supported by NEDO)

The fundamental experiments with RCEM (Rapid compression and expansion machine) clarified the influence of the fuel dilution and reforming into hydrogen on the minimum laser power to ignite. And, the wear of target was measured under several conditions. The results predict that the durability will be over 10,000 hours under minimum ignition condition. By the tests of laser transmission optical system, the laser beam shot out of the laser equipment main body was transmitted to the target of each cylinder through an optical fiber and plasma could be generated on the target. Then engine tests in which fuel methane was diluted by nitrogen to imitate low-quality gas were conducted using a cylinder of a test engine. As the results, it was confirmed by the increase of conversion ratio from methane to hydrogen for pre-combustion chamber fuel that the misfire limitation for low-grade fuel was enlarged. Finally in the total system verification tests the engine performance was evaluated when fuel methane was diluted in large quantity (CH4:30%,N2:70%). The output power is about 200kW. It was found that the thermal efficiency was 39.3 %.

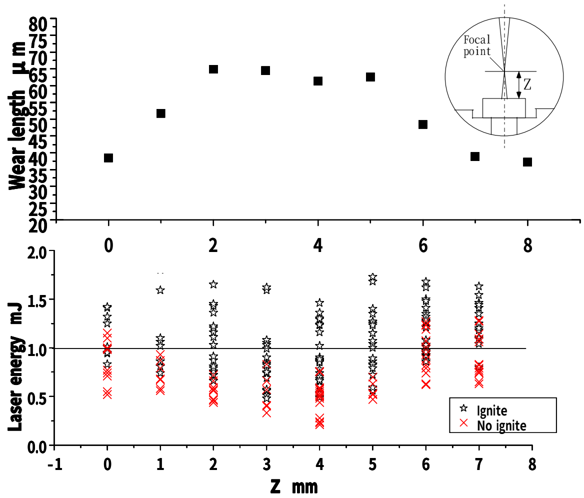


Fig.14 Wear of target and minimum laser energy to ignite

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