47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition
5 - 8 January 2009, Orlando, Florida

AIAA 2009-223

Microwave Enhanced Ignition Process for Fuel Mixture at Elevated Pressure of 1MPa

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A new plasma generation technique that uses spark discharge and microwaves is proposed. The spark discharge generates a small plasma source enhanced by microwave power, increasing its volume and brightness. Using this new technique, plasma was produced successfully, even at a pressure of 2.0 MPa. As the microwave plasma was generated, the emission intensity of OH radicals increased to 300 times greater than with the spark discharge alone. To apply this technique as the ignition source in a gasoline engine, a prototype spark plug was developed. The spark plug contained a miniature microwave antenna and could generate plasma at pressures up to 1.0 MPa. Combustion experiments were performed using compression–expansion and single-cylinder research engines. The compression–expansion engine had a quartz window at the bottom of the cylinder and flame images, the pressure signal, and the emissions from OH radicals could be recorded. With plasma-enhanced combustion, a large flame kernel formed and the flame propagation speed increased. In the single-cylinder engine, the combustion stability improved and the microwave-enhanced ignition increased the lean limit from 19.3 to 24.1.

I. Introduction

Improved efficiency and a reduction in greenhouse gases are critical issues in the development of internal combustion engines. Figure 1 shows the change in the average CO_2 emissions of cars sold in the European Union (EU) and the distance to the target if the historic rate of improvement does not change.[1] The CO_2 emissions from automobile engines were reduced from 185 g/km in 1995 to 165 g/km in 2001, but have remained at the same level since 2001. Passenger cars account for about 12% of the carbon emissions in the EU, and the European Commission adopted a proposal for legislation to lower the average CO_2 emissions of new passenger cars on 19 December 2007, setting a target for the average emissions from new cars sold in the EU-27 to reach 120 g CO_2/km in 2012.[2] The regulation sets the limits of permitted CO_2 emissions for new cars according to the mass of the car. Figure 2 shows the average mass and CO_2 emissions of new cars manufactured in 2006 and the limits proposed for 2012. In 2006,

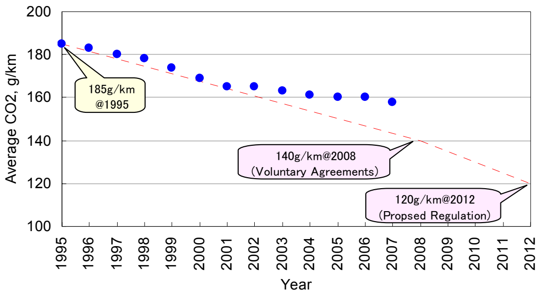

Fig. 1 Progress over time in average CO_2 emission of cars sold in European Union (EU), and distance to target.[1,2]

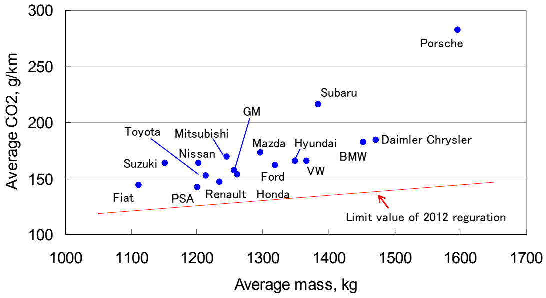

Fig. 2 Average mass and CO_2 emission of new cars manufactured in 2006 and limit value of 2012 regulation.[1,2]

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however, no manufacturer had achieved these limits.

In spark ignition (SI) engines, lean combustion is one way to lower exhaust and CO_2 emissions while improving efficiency. Much effort has been made to promote combustion in SI engines by trying to extend the lean limit of stable combustion. The period of early flame kernel development strongly influences engine performance and the emission characteristics of SI engines.[3,4] However, the initial flame kernel becomes unstable at lean operating conditions, as shown in Fig. 3. To reduce the cyclic variation, an innovative ignition source that can form a stable initial flame kernel under lean conditions is imperative, and lowering CO_2 emissions by gas turbine and jet engines is also important.

Plasma-assist combustion is an intense, stable ignition source, and several studies of it have been reported.[5–23] While, conventional plasma ignition uses a pulsed laser or microwave to create plasma, laser ignition requires a high-power laser and a large system, thus posing barriers to practical application. To generate plasma under high pressures using microwaves, very high-power microwaves must be focused on a small point.

This study developed a novel microwave-enhanced ignition system that can be applied to engine systems without changing existing engine designs. The novel ignition system can control ignition delay and improve flame propagation at low cost. Figure 4 shows microwave-enhanced ignition in an automobile.

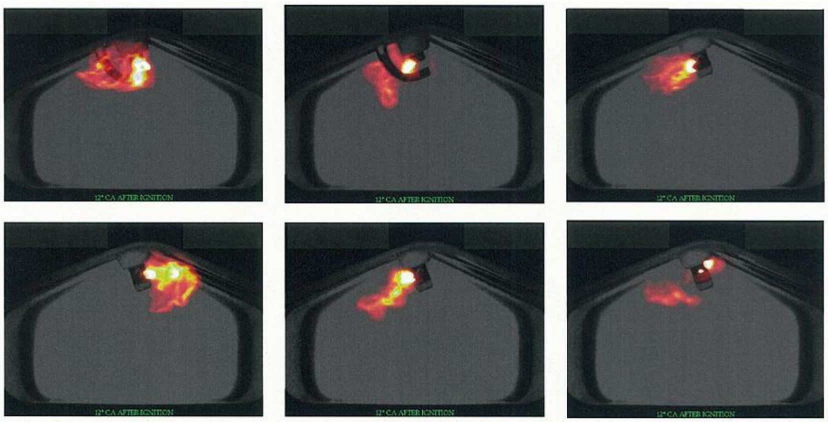


Fig. 3 Cycle-by-cycle variations in the early stages of combustion.[3]

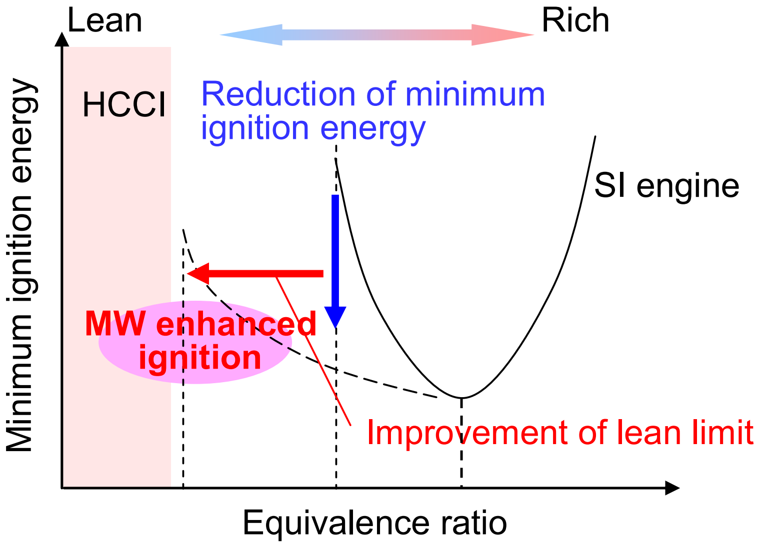


Fig. 4 Target of the microwave enhanced ignition.

The initial flame kernel development is stable with microwave-enhanced ignition, reducing the cycle-by-cycle variation. As a result, microwave-enhanced ignition increases the lean limit, improving fuel consumption. In addition, the application of this method to a variety of fuels was examined, revealing homogeneous charge compression ignition (HCCI), the inhibition of knock in the high-load region, and the reduction of total hydrocarbons during a cold start.

In this study, a new plasma generation technique that uses a combination of spark discharge and microwaves was developed. This technique was applied as an intense, stable ignition source in a gasoline engine, even under lean conditions. With our method, plasma was created by a spark discharge and increased by the microwave power, producing nonthermal plasma. Moreover, generating plasma under high pressures using a spark plug is easy. We successfully produced plasma at an air pressure of 2.0 MPa.

To apply the plasma generation technique to an engine system, the spark plug must contain a microwave antenna. Thus, a prototype of a microwave-enhanced ignition plug was developed. Combustion experiments with compression–expansion and single-cylinder spark ignition engines were performed. The principles of the plasma generation technique are described in Section II and a prototype of the microwave-enhanced ignition plug and experimental setup are presented in Section III. The experimental results are given in Section IV.

II. Principle of plasma generation technique

Plasma has a high potential to instigate chemical reactions that cannot progress under normal environmental conditions because it contains high-energy electrons and active radicals. For example, OH radicals, which have a very high oxidization potential, are generated by the collision of high-energy electrons and H_2O molecules.

Many methods can be used to generate plasma using radio frequencies or microwaves. However, most of them can form plasma in a vacuum chamber only. In the standard process of plasma generation, electrons are accelerated by an electric field, and they then ionize other atoms and molecules via collisions. For this process to progress, an electric field high enough to accelerate the electrons to energies above the ionization potential of the atoms and molecules is needed. In a vacuum, the electrons can be accelerated easily because the mean free path is relatively long. However, the mean free path is short under high pressures. Consequently, a very large energy is needed to form an electric field high enough to accelerate the electrons.[24,25]

Generally, plasma can absorb electromagnetic waves. As an example, consider laser-induced plasma. Figure 5 shows the relationship between the incident energy and transmitted energy for laser-induced plasma.[26] When a short-pulse laser is focused into air or gases, the laser beam creates a high-intensity field associated with high electric fields in the focal region, resulting in localized plasma. In the figure, the events without breakdown are plotted with crosses and the events with breakdown are plotted with circles. If the incident and transmitted energies are the same, then breakdown has not occurred. If breakdown occurs, the transmitted energy falls below the incident energy because the laser plasma absorbs incident energy.

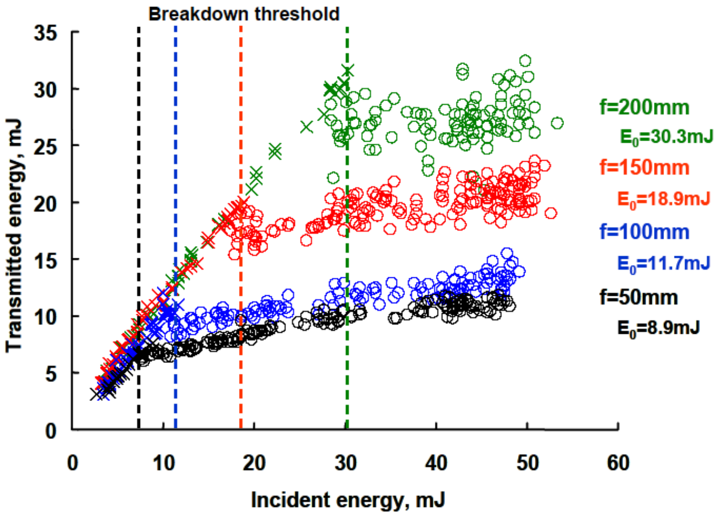


Fig. 5 Relation between incident energy and transmitted energy.[26]

If plasma exists, we can provide energy to the plasma using electromagnetic waves. The small spark formed by a spark plug is also plasma. The spark plugs normally used in automobiles discharge easily, even in the engine cylinder. Since the gap between the electrodes is very small, the spark plug can discharge with a small input energy (<50 mJ). However, the spark plasma is very small (*i.e.*, it is a micro-plasma). To expand the micro-plasma, microwave power was applied. Since the plasma contains many electrons, the microwave power is effectively absorbed and the plasma becomes larger. The magnetron from a microwave oven, which produced microwaves at a frequency of 2.45 GHz, was used. Magnetrons for microwave ovens are very efficient and reasonable priced, so that compact, economical plasma generation systems can be constructed easily.

Figure 6 illustrates the concept of microwave plasma combustion. A locally intensified microwave field is formed by a microwave antenna. The microwave power is less than the minimum ignition energy. However, a small plasma source is generated by a spark discharge using a standard automobile spark plug and ignition coil. Consequently, the small plasma source absorbs the microwave power and is expanded and sustained by the microwaves, providing many radicals and enhancing combustion.

To concentrate the microwave power at a local point, the shape and size of the cavity and antenna were optimized with field simulations. The calculated result is shown in Fig. 7. The chamber was ϕ75 mm in diameter and 130 mm high. The antenna was cone-shaped and 90 mm high.

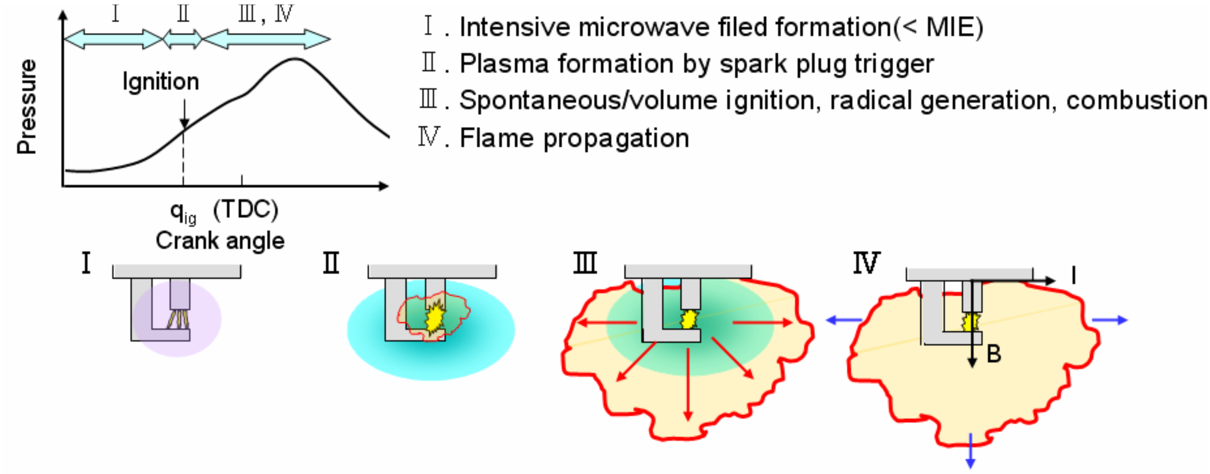


Fig. 6 Concept of microwave plasma ignition engine.

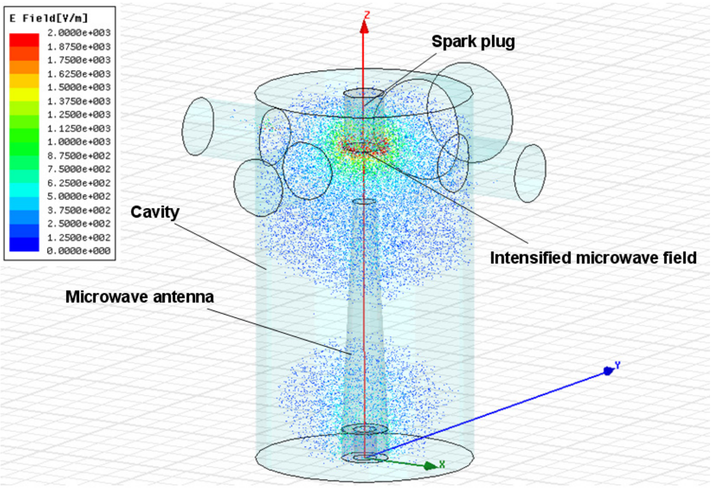


Fig. 7 Calculation result of field simulator. Intensified microwave field is formed above the antenna.

Figure 8 shows photographs and emission spectra of plasmas generated by spark discharge only and those expanded by microwaves at atmospheric pressure. As the microwaves were injected, many OH radicals were generated, and the emission intensity from the plasma increased to 300 times that with the spark discharge alone. The new technique uses a spark discharge to generate the plasma source. A spark plug can easily form a micro-plasma at a pressure of 2.0 MPa. On providing microwave power to the micro-plasma, nonthermal plasma is generated easily, even at high pressures. Plasma at air pressures of 2.0 MPa were successfully generated, as shown as Fig. 9.

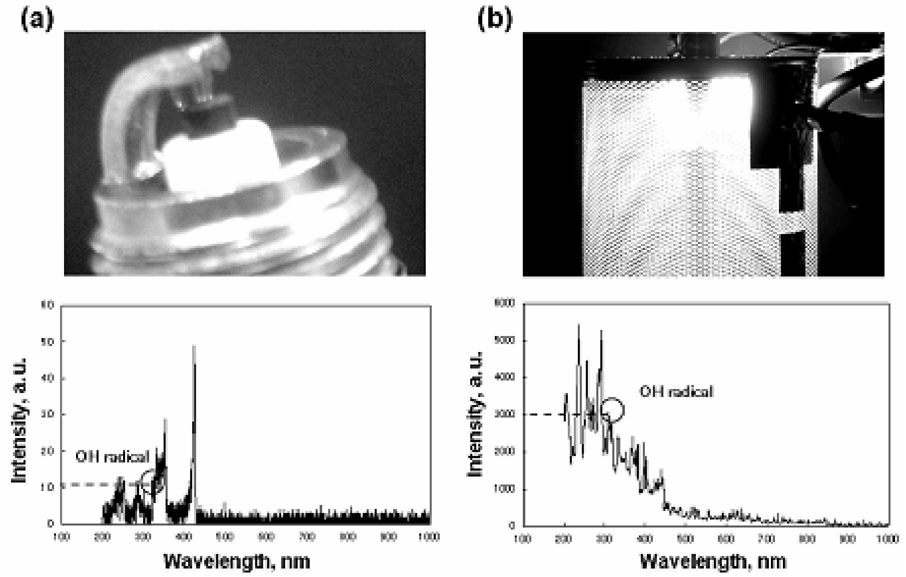


Fig. 8 Images and emission spectra of plasma (a) generated by only spark plug, (b) enhanced by microwave.

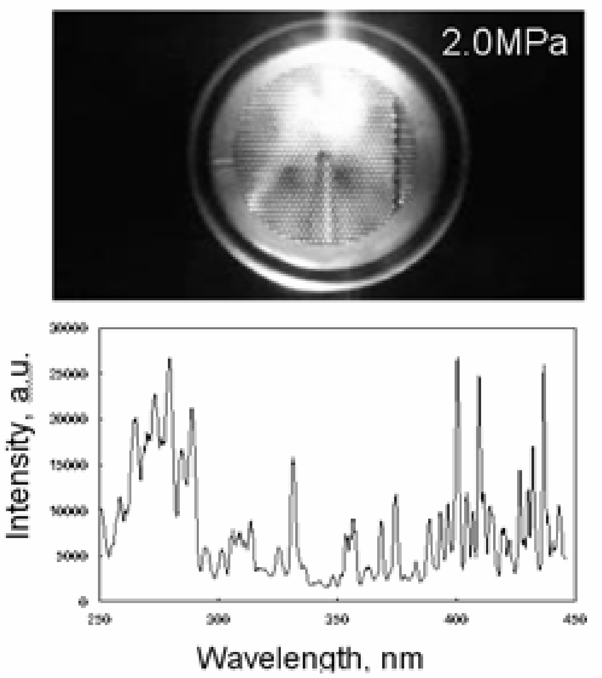


Fig. 9 Images and emission spectra of plasma generated in 2.0 MPa.

III. Experimental setup

A. Development of an antenna in a spark plug

To generate and sustain plasma in an engine cylinder without changing the existing engine system, a microwave antenna was built into a spark plug. Figure 10 shows the prototype spark plug containing a microwave antenna made from tungsten wire with a diameter of ϕ1 mm set around the center electrode. The shape and length of an antenna are very important parameters because they greatly affect the characteristic impedance and performance of the antenna. Figure 11 shows a photograph of plasma generated by the prototype spark plug installed in high-pressure chamber taken through a quartz window. Plasma was produced successfully at a pressure of 1.0 MPa.

Fig. 10 Prototype of spark plug having a microwave antenna.

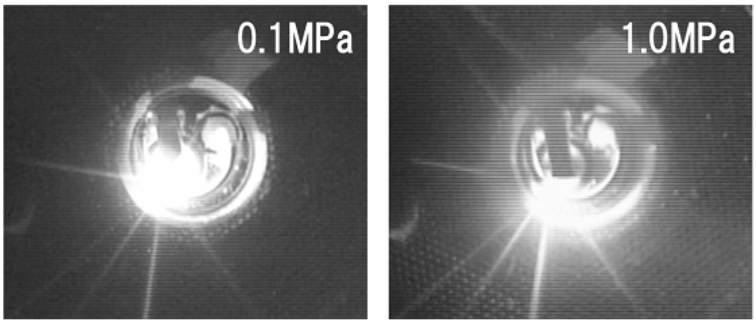


Fig. 11 Plasma generated by the prototype spark plug.

B. System set-up

Figure 12 shows a schematic diagram of the microwave plasma combustion system. The system consists of a spark plug, microwave transfer system, and control system. The magnetron from a microwave oven was used as the microwave oscillator. The spark plug contained a microwave antenna and generated plasma in the engine cylinder. A microwave transfer system transmitted the microwave power from the oscillator to the antenna via a coaxial cable. Using a coaxial cable, the magnetron can put placed some distance from the engine. Commercial magnetrons were matched to waveguide transfer. Then, a waveguide-coaxial converter was used, as shown in Fig. 12.

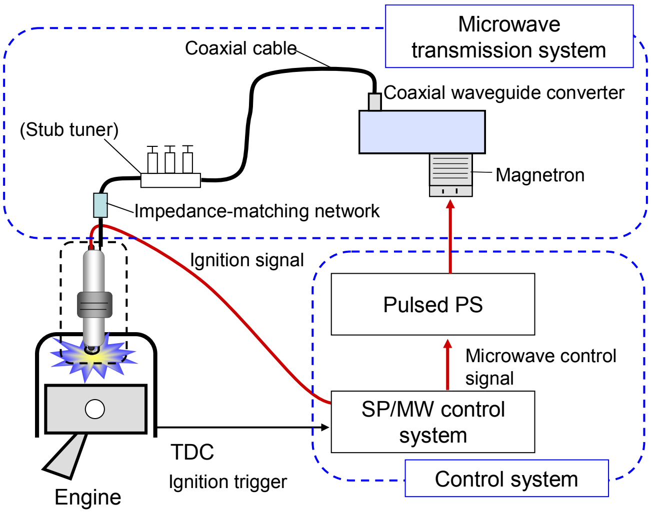


Fig. 12 Microwave plasma ignition system.

The control system synchronized the spark timing and microwave radiation. The timing and duration of microwave radiation were controlled by the spark plug/microwave (SP/MW) control system. Figure 13 shows the timing chart for the spark and microwave signals. The SP/MW control system worked with reference to a trigger signal set to a given crank angle, which was output from the electronic control unit (ECU). Spark and microwave control signals were sent to a pulsed power supply according to the delay from the trigger and desired duration. The spark and microwave signals could be determined individually. The plasma characteristics could be regulated by controlling these signals. Impedance matching between the antenna and coaxial cable is important to reduce transmission loss and improve the radiation efficiency. Three stub tuners were used for impedance matching. The reflected power was reduced to less than 10% by adjusting the tuner based on the monitored reflected wave using a network analyzer.

IV. Result and Discussions

A. Compression-expansion engine

A specially designed compression–expansion engine that can only be fired once was used as the test engine for the experiments.[27] The specifications of the compression–expansion engine are shown in Table 1. The engine had a bore of 78 mm, stroke of 85 mm, and compression ratio of 9.5. The cylinder and mixture tank were initially charged with a homogeneous methane–air mixture. The compression–expansion engine provided optical access via an extended piston and quartz window. Combustion inside the cylinder was visualized using a high-speed video camera.

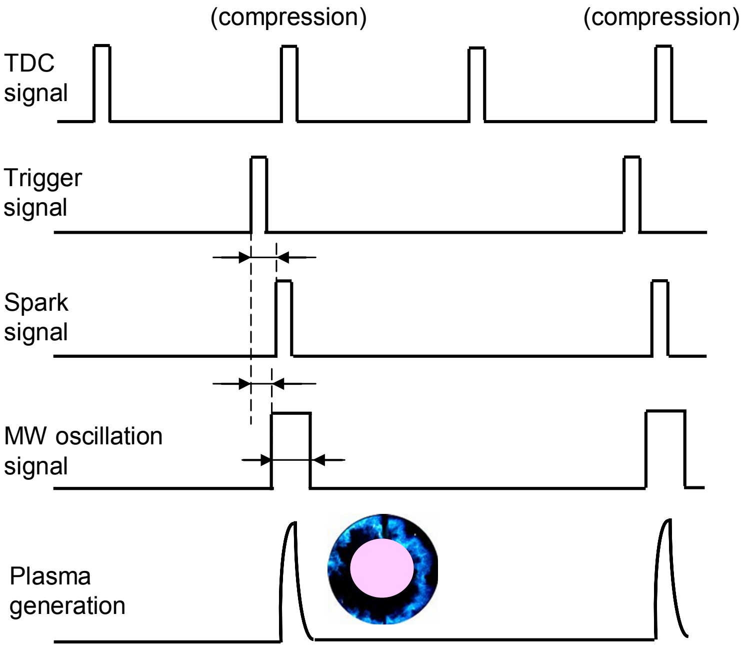


Fig. 13 Time chart of plasma ignition.

Table 1 Specifications of compression-expansion engine.[27]

Type	Compression-expansion engine (Bottom view)
Number of cylinders	1
Bore	70 mm
Stroke	58 mm
Displacement	223 cc
Compression ratio	9.5

Figure 14 shows photographs of the flames with spark ignition and microwave plasma ignition. The fuel was C3H8 and the equivalent ratio was ϕ = 1. The initial pressure and engine speed were 600 kPa and 600 rpm, respectively. The ignition timing was set to be 12° before top dead center (BTDC).

In the case of normal spark ignition, spark discharge was observed at –14.2° after top dead center (ATDC). The flame kernel was formed at –7.0° ATDC, and then the flame propagated (–0.2° ATDC). In the case of plasma ignition, intense light from the plasma was observed shortly after ignition. Then, a large flame kernel was formed by the plasma at –7.0° ATDC. At –0.2° ATDC, the flame had propagated to the limit of the viewing region. Using microwave plasma as the ignition source, the initial combustion occurred earlier.

Figure 15 shows the flame area, pressure, and intensity of OH radical emission for the case ϕ = 1. The magnetron worked and radiated microwaves from –15.6° to –8.4° ATDC. Plasma was generated by spark discharge at –12° ATDC and enhanced by the microwaves. With plasma ignition, intense emission from OH radicals was observed. In addition, the rate of pressure rise and the peak pressure were higher than with spark ignition. This indicates that the microwave plasma generated many OH radicals, which affected ignition, development of the initial flame kernel, and flame propagation. The initial combustion occurred earlier with plasma ignition and the plasma effect was greater under the lean condition.

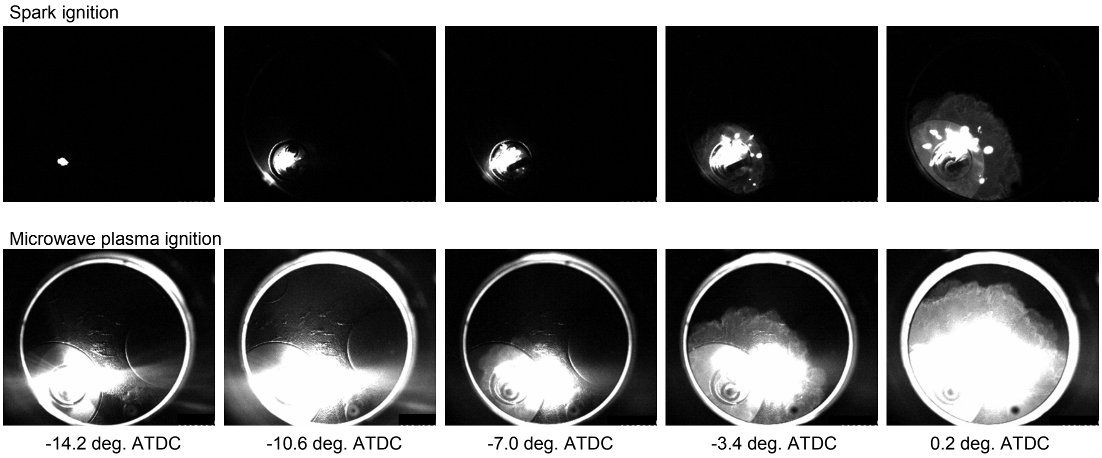


Fig. 14 Comparison of flame images (ϕ = 1).

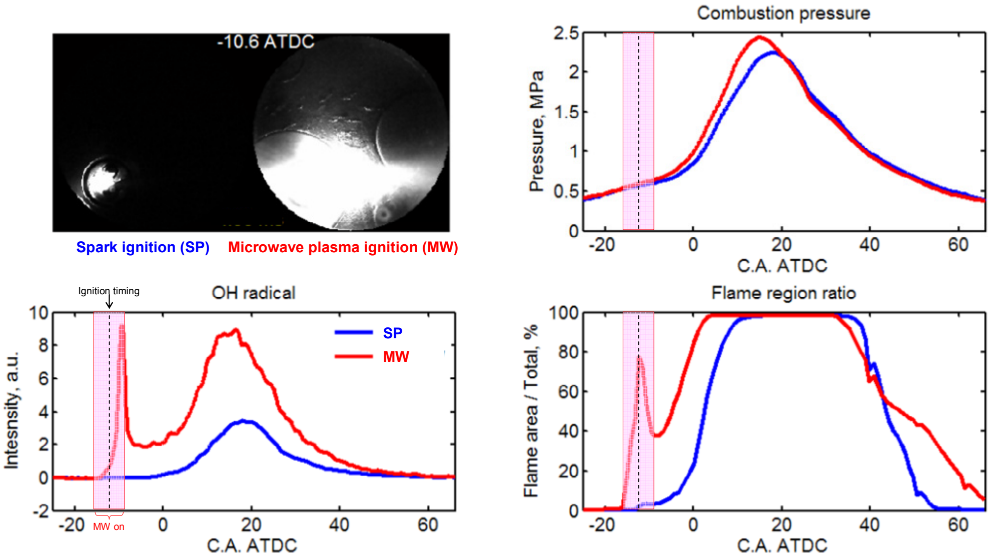


Fig. 15 Comparison of pressure and OH radical intensity in the cases of ϕ = 1.

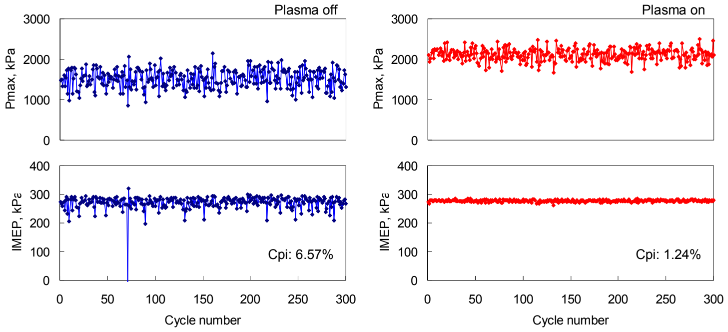
B. Single Cylinder Test Engine

To evaluate the effect of the plasma, measurements were made using a water-cooled, four-stroke-cycle gasoline AVL research engine with four valves. Regular gasoline was used as the fuel. The specifications of the engine are given in Table 2. The test was at a constant indicated mean effective pressure (IMEP) of 275 kPa at 2000 rpm. The effects of microwave-enhanced ignition on the lean limit, fuel consumption, and exhaust emissions were evaluated

Figure 16 compares the cyclic variation of the pressure peak and IMEP between spark and plasma ignition. Figure 17 shows pressure–volume (P–V) curves under the same operating conditions measured at a mean IMEP of 275 kPa and an air/fuel ratio (A/F) of 20; the minimum best torque (MBT) was achieved at 2000 rpm. With conventional spark ignition having a cyclic variation coefficient of IMEP (COV_{IMEP}) of 6.57%, the combustion was unstable. In contrast, the microwave-enhanced ignition reduced the variance in the peak pressure and stabilized the IMEP (COV_{IMEP} = 1.24%). Consequently, microwave-enhanced ignition could reduce the combustion instability under lean conditions. The OH radicals supplied by the plasma promoted immediate combustion. Consequently, the initial flame kernel was larger and the flame development was enhanced in the early stage with plasma. For the cases shown in Figs. 16 and 17, the cylinder pressure at ignition was 0.15–0.20 MPa. The prototype spark plug could generate plasma at 1.0 MPa, as shown in Fig. 11. Plasma was generated in a stable manner in the engine cylinder, which stabilized the development of the initial flame kernel.

Table 2 Specification of single-cylinder engine.

Type	Water-cooled, 4-stroke-cycle, 4-valves
Number of Cylinders	1
Bore	86 mm
Stroke	86 mm
Displacement	499.6 cc
Compression Ratio	9.5



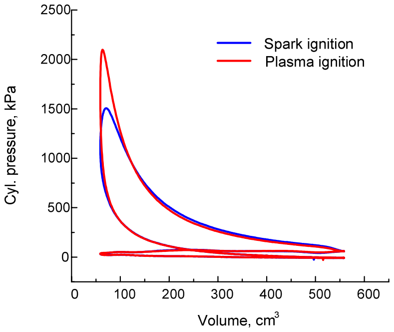


Fig. 16 Comparison cyclic variations peak pressure and IMEP between spark ignition and plasma ignition.

Fig. 17 Comparison of p-V diagram in the case of 2000rpm and IMEP=275kPa.

Figure 18 shows the effect of spark and microwave plasma ignition on COV_{IMEP}, fuel consumption, and exhaust emission (CO, CO_2, and NO_x) at 2000 rpm. With spark ignition, the A/F was 17, and the COV_{IMEP} increased dramatically. In contrast, with plasma ignition the COV was essentially constant until A/F = 22. The lean limit of spark ignition was 19.3. Steady combustion was obtained with microwave plasma combustion, and the lean combustion limit was 24.1 in the range that did not ignite with the spark. Under these operating conditions, plasma ignition can be extended to lean limits of A/F of about 5. On comparing fuel consumption, the spark ignition condition had a minimum at A/F = 19 and the fuel consumption became poorer under leaner conditions. However, plasma ignition reduced the fuel consumption as A/F increased. Since combustion is unstable with conventional spark ignition at A/F >18, CO emissions increase, but plasma ignition reduced CO, CO_2 and NO_x emissions as A/F increased.

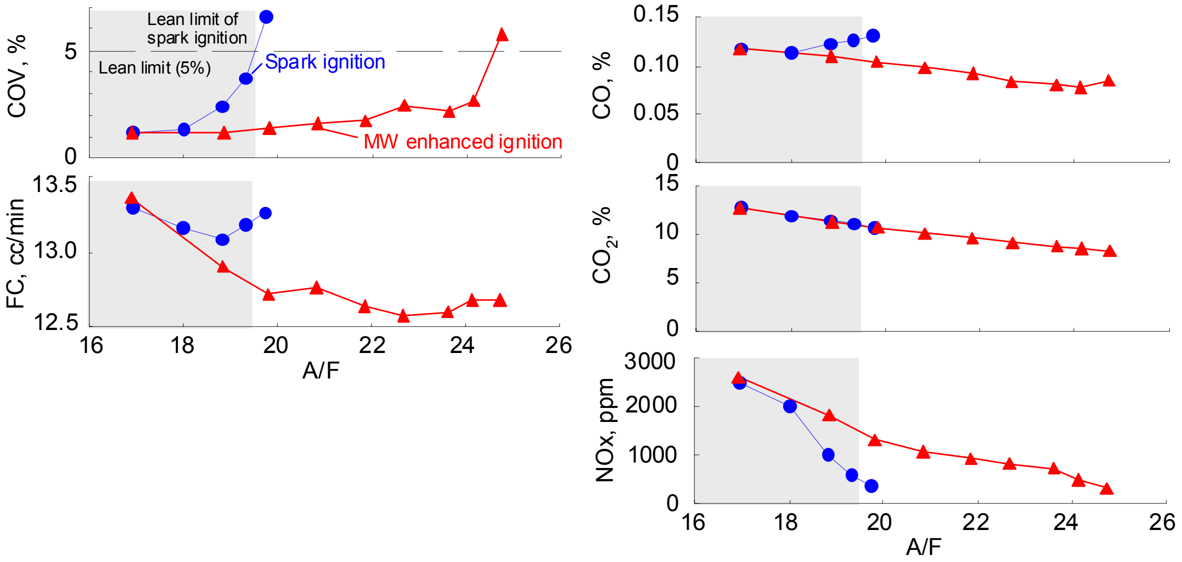


Fig. 18 the effect of spark ignition and microwave plasma ignition on COV_{IMEP}, fuel consumption and exhaust emission.

V. Conclusion

An innovative plasma generation technique was developed and used as the ignition source in a SI engine. This technique generates plasma easily, even at pressures exceeding 1.0 MPa. In this technique, a spark discharge first generates a small plasma source, and then microwaves radiated to the plasma source provide energy that is absorbed by the plasma, which then expands. The experiment used an inexpensive commercial microwave oven magnetron that produces microwaves at frequency of 2.45 GHz. In a gasoline engine, the cylinder pressure at ignition is usually lower than 1.0 MPa, while our plasma-generation technique can generate plasma at pressures exceeding 1.0 MPa. Consequently, plasma can be formed in the engine cylinder easily and stably. To apply this technique to a SI engine, a spark plug containing a microwave antenna was developed. The spark plug could generate plasma at pressures of 1.0 MPa. Combustion experiments were performed in compression–expansion and single-cylinder research engines. Using a high-speed camera, plasma generation and high-intensity OH radical emission were observed in the cylinder. The microwave-enhanced ignition enlarged the initial flame kernel, increasing the peak pressure earlier than with conventional spark ignition. The microwave plasma provided many OH radicals and served as an intense, stable ignition source. At IMEP = 275 kPa, the plasma increased the lean limit from 19.3 to 24.1 in the single-cylinder research engine. Since microwave-enhanced ignition improved combustion stability, even under lean conditions, CO, CO_2, and NO_x emissions were reduced as the A/F increased.

Acknowledgment

This work was supported by the New Energy and Industrial Technology Development Organization (NEDO), Strategic Development of Energy Conservation Technology/ Preparatory Research Phase of Fundamental Technology Development for Energy Conservation.

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