Problems of Plasma Ignition System

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Abstract

DENSO TEN joined the development of a microwave-based powerful ignition system (plasma ignition system) which was a core technology for realizing 50% of thermal efficiency of an internal-combustion engine from FY2013 to the end of FY2016. We would like to report the summary of technology and knowledge which we have obtained through the development of three and a half years.

In plasma ignition system by adding microwave irradiation function to the current spark ignition system, for which DENSO TEN joined the development, when microwave was irradiated, the DC electric field component which remains in the spark ignition system limited the diffusion direction of non-equilibrium plasma. As a result, passing through electrical shortage between spark plug electrodes, and electrode with overheated status by a big current is required for plasma volume that delivers enough ignition performance. There is a principled factor here to block to balance ignition performance with durability performance in our plasma ignition system.

This paper describes the principled factor to block to balance ignition performance with durability performance, and indicates the direction of the solution.

1. Introduction

Spark ignition system,which was first practically used in 1860, has been developed and improved as a main ignition system of all internal-combustion engine. And due to introduction of direct ignition system in which each cylinder has an ignition coil of which ignition timing is controlled by engine control ECU in the end of 1980's, the spark ignition system works as the perfect maintenance-free system in the present day.

On the other hand, for continually complying to emission gas regulation and fuel consumption regulation which have been tightening every year, drastic improvement of thermal efficiency in internal-combustion engine is mandatory. As for the improvement of thermal efficiency, it is important to realize ultra-low lean-burn which reduces fuel amount used for combustion, in addition to reduce losses such as machine loss of engine and cooling loss. However, lean mixture which can be ignited by spark plug in spark ignition system almost reaches the limit of fuel amount 1 per air amount 25 (A/F equals to 25). At the current situation, stable ignition performance to leaner mixture than A/F 25 is hopeless. The following strong ignition systems are proposed to realize ultra-low lean-burn.

- Large ignition coil：
  To maximize the energy of spark itself.
- Continuous ignition system：
  To inject energy into secondary coil during secondary discharge in order to keep glow discharge of spark ignition for long period.
- Microwave plasma-assisted ignition system：
  To be ignited widely with plasma enlarged by injection of microwave at the timing of spark ignition.
- Laser breakdown ignition system：
  To be ignited by high temperature plasma generated in any place in the combustion chamber by collecting laser beam with a convex lens.
- HCCI (Homogeneous Charge Compression Ignition)
  Homogeneous charge compression ignition system without spark ignition.

However, each of these systems has advantages and disadvantages. None can secure stable quality for practical use at the moment. DENSO TEN decided to join the development of microwave plasma assisted ignition system, in view of expectation to materialization by the development of elemental technology such as semiconductor and others under the situation in 2013, and to improvement of ignition performance by three-dimensional ignition.

2. DENSO TEN's roll for the development of plasma ignition system

Ignition system of which the development DENSO TEN joined is called microwave plasma assisted ignition system in general. We named this system plasma ignition system.

This plasma ignition system is a system based on the result of "Research and Development of Microwave Plasma Combustion Engine" which was mainly performed by Imagineering, Inc. (Chuo-ku, Kobe president and representative director: Mr. Yuji Ikeda) as part of business of New Energy and Industrial Technology Development Organization (NEDO) of National Research and Development from FY2006 through FY2013.

DENSO TEN joined the development for realizing a mass production module which could be mounted on vehicle, based on the principle and the prototype system materializing the principle obtained from the above research and development since FY2013.

3. System Structure

The plasma ignition system is the structure involving direct ignition as is which can output both spark (by the high voltage) and microwave from a spark plug tip by mixing microwave of 1kw class 2.45GHz in the pathway of a high voltage supplied to the spark plug from the second coil of the ignition coil as shown in **Fig. 1**.

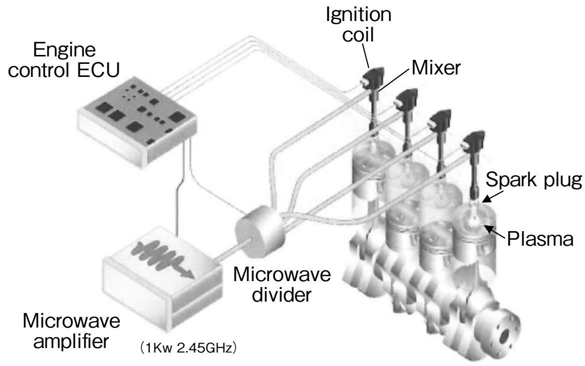

Fig. 1 Configuration of Plasma Ignition System Overview

A mixer which mixes high voltage with microwave is configured so as to couple microwave on the central electrode which transfers high voltage with the cylindrical cavity resonator around as shown in **Fig. 2**. By setting the cavity resonator on microwave pathway, high voltage is prevented from flowing backward to microwave pathway. Also microwave superimposed on central electrode is prevented from flowing backward to ignition coil direction by setting choke at the central electrode part on the ignition coil side compared to the location of cavity resonator. Thus mixer is configured to transfer energy only in the direction toward spark plug from input terminal for both high voltage and microwave.

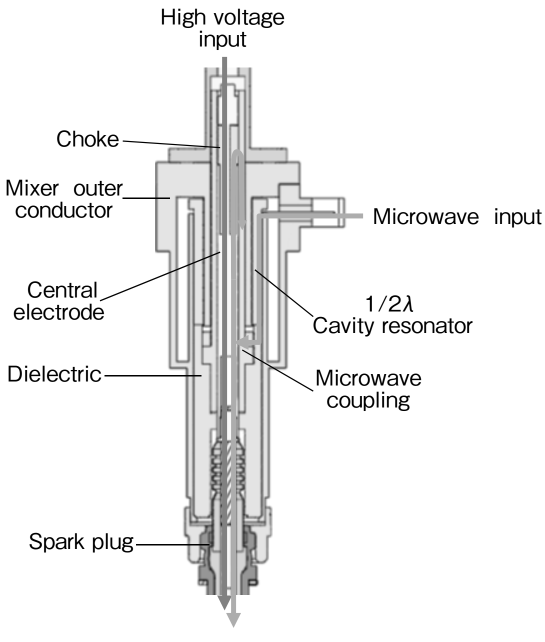

Fig. 2 Structure of Mixer Section Overview

The amplifier section which generates microwave of 1kw class 2.45GHz consists of PLL which generates 2.45GHz signal, Gate switch which makes microwave output intermittent, VGA (Variable Gain Amplifier) which makes fine adjustment to output power, high frequency power amplifier which amplitudes microwave output power up to 1kw class, and MCU (Micro Control Unit) which controls timing, pulse width, duration, and output level. As shown in **Fig. 3**, this system is designed to control microwave output optimally for each engine operation status in accordance with spark ignition which is controlled by engine control ECU.

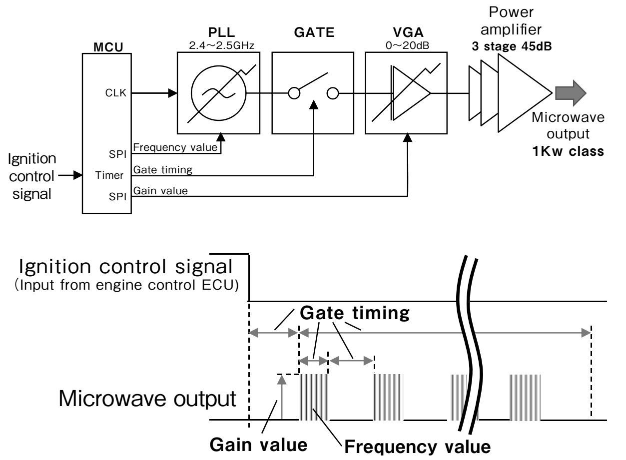

Fig. 3 Function of High Frequency Power Amplifier Overview

Fig. 4 shows the appearance of system module for engine bench evaluation test which DENSO TEN developed in FY2016. As for experimental evaluation such as engine bench etc., a stub tuner is installed to have impedance matching of microwave pathway. However, considering mass production module for on-vehicle mounting, further downsizing of mixer and amplifier are required with abolition of the stub tuner and coaxial cable. **Fig. 5** shows the target image designed as mass production module.

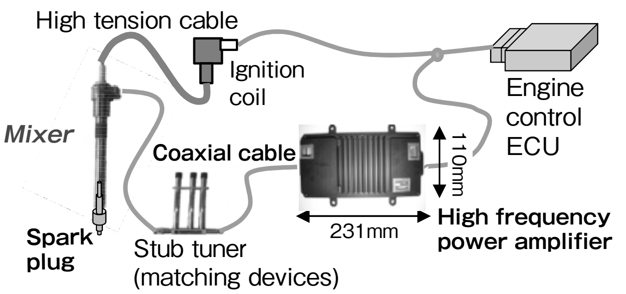

Fig. 4 System Module developed by DENSO TEN in FY2016

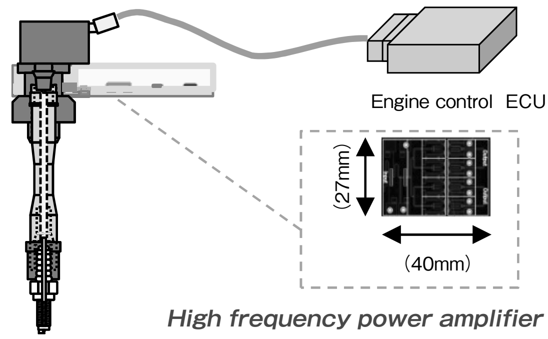

Fig. 5 Configuration of Mass Production Module (Development target at the time)

4. Aiming of Strong Spark Ignition System

Table 1 shows the performance target of plasma ignition system assuming mass production and the result reached in the end of FY2016.

Table 1 Performance target of Plasma Ignition System and Development Result

Study item	Evaluation item		Judgment value (good condition)	Evaluation Environment: Constant volume chamber		Evaluation Environment: Engine	Study result	
				Dis-charge	Combus-tion	single cylinder		
Compatibility Ignition Performance and Durability Performance	Ignition performance	Radical emission intensity (discharge only)	1.5 times spark ignition	■			○	100 times or more
		Burning velocity (10% burning period)	1.3 times spark ignition		■		×	About 1.1times
		A/F lean limit (single cylinder)	3.5 or more for spark ignition			■	—	—
	Plug Durability performance	Number of serial normal discharge (discharge only)	36million times	■			×	About 0.2 million times
		Number of serial normal discharge (discharge and combustion)	36million times			■	—	—

If we consider the QCV of engine system, the realization of combustion in mixture of fuel amount 1 per air amount 30 (air/fuel = 30) is required, which doesn't need expensive auxiliary equipment such as NOx catalyst possibly installed for lean burn. We settled the target amount of air/fuel improvement was 3.5 after taking account of the improvement amount by engine mechanism itself. Also as evaluation index correlated with air/fuel in the ignition limit by spark, we set 10% combustion period in a constant-volume chamber.

36 million ignitions of plug durability performance are assumed for 60 thousand km driving by normal vehicle. Current 150 thousand km and 200 thousand km warranty are ideal, but we settled acceptable minimum warranty distance as the first step target for mass production vehicle.

As shown in the result in the end of FY2016, the problem of ignition plug durability performance includes fatal i.e. principled issue in this plasma ignition system.

5. Contradiction between Ignition Performance and Durability Performance

Fig. 6 shows the measurement result of abrasion loss of spark plug tip electrode under a certain environment. (Pressure at ignition 0.4MPa, gas composition: Air)

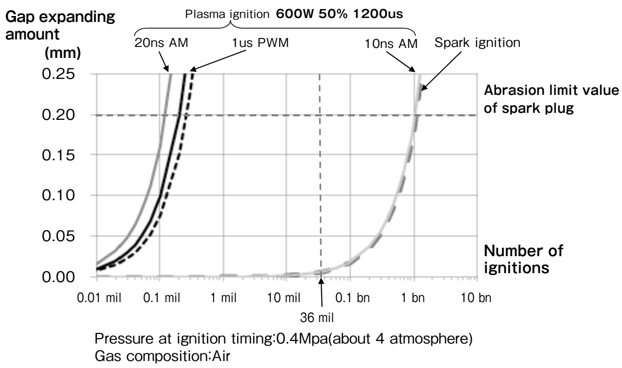

Fig. 6 Abrasion Loss of Spark Plug Tip Electrode

Horizontal axis is the number of ignitions, vertical axis is the variation of gap dimension between electrodes (gap expanding amount) equivalent to abrasion loss of electrode. 0.2mm of gap expanding amount is the limit of spark generation. The graph shows the number of ignitions at the time when the gap expanding amount reached the limit 0.2mm in case of repeating various ignition control conditions.

In case of current spark ignition with ignition coil only, as the number of ignition to reach the abrasion limit of spark plug is about 1.1 billion, it has enough abrasion performance compared to our target ignition number 36 million times. On the other hand, with the assistance by microwave in plasma ignition system, the results are separated to two groups. Namely in one group, 100 thousand ignitions lead to the abrasion limit of spark plug and in other group, around 1 billion ignitions are taken for that.

Microwave-assisted method with 1us PWM is the method with which the combustion improvement effect is confirmed in actual engine. As for microwave-assisted power waveform with 1us PWM, period is 1us, ON duty is 50% and peak power at ON is 600W as shown in **Fig. 7**. Because very short period power switching is impossible due to property of our device, we use AM modulation as an alternative method. Then, the amount of energy which is assisted by microwave for 1200 us is the same for both PWM method and AM method.

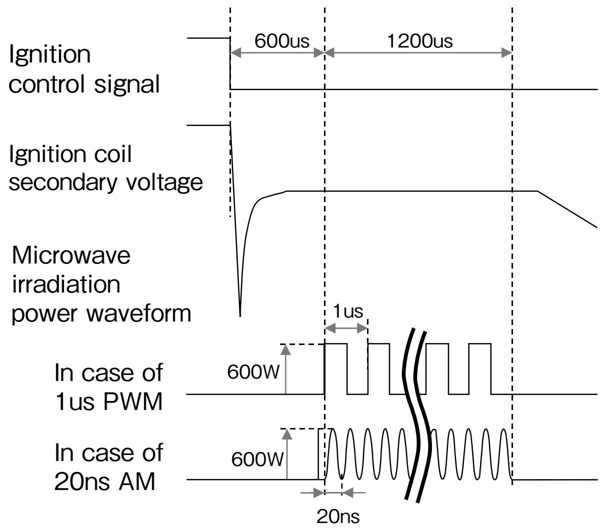

Fig. 7 Waveform of Microwave-assisted Power

We found from **Fig. 6** there was a borderline to divide abrasion durability of spark plug to good and bad in very short period such as between 10 and 20ns of switching cycle of microwave-assisted power. **Fig. 8** shows the observation results of one-by-one ignition operation phenomenon to find out the difference between 20ns AM method and 10ns AM method.

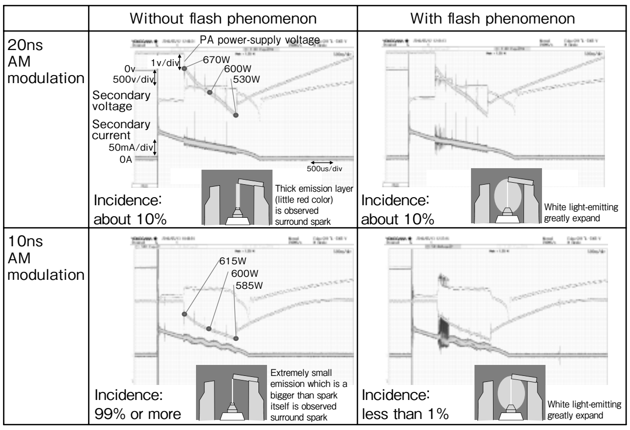

Fig. 8 Operation Phenomena by One Ignition

Operation phenomena by one ignition are the same for both 20ns AM method and10ns AM method. There were two phenomena, which were flash phenomenon and no flash phenomenon, and the difference between the two is for the frequency of flash phenomenon. One of 20ns AM, of which abrasion loss is large, is high and one of 10ns AM, of which abrasion loss is small, is extremely low. **Fig. 9** shows aspect of plasma at spark plug tip by continuous photograph. It is found the presence or absence of flash phenomenon is depending.

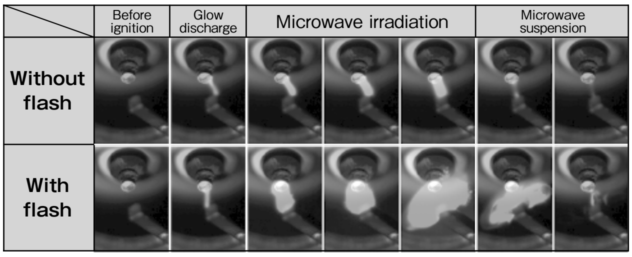

Fig. 9 Plasma at Spark Plug Tip (Continuous Photograph)

The each waveform in **Fig. 8** shows the changes of secondly voltage of spark ignition, secondly current, and supply voltage of microwave amplifier for the presence or the absence of flash phenomenon respectively. The timing for irradiation of microwaves is shown in **Fig. 7**. It is irradiated for 1200us after waiting time of 600us from ignition start timing. Under a constraint on the device, the power supply voltage of microwave amplifier will drop in accordance with the irradiation of microwave, and the output power of microwave also will drop in proportion to that power supply voltage. However experimental setting of average power is 600W during irradiation of 1200us as shown in **Fig. 8**.

The difference between the presence and the absence of flash phenomenon is the change of secondary voltage and current. In case of no flash phenomenon, secondary voltage maintains about -900v after high voltage passing for the first insulation breakdown until 600us where irradiation of microwave starts. When irradiation of microwave starts, the average voltage becomes -500v for 20ns AM, and -600v for 10ns AM, and a high-frequency current superimposes on the secondary current simultaneously. However, the frequency of these voltage and current are high, actually 2.45GHz, of which the peak-value cannot be grasped by an oscilloscope. And those continue without big change until the end of irradiation of microwave. On the other hand, in case of flash phenomenon, the average secondary voltage increases by -250v for 20ns AM, and -350v for 10ns AM, and it seems there is a superposition of secondary current greater than no flash case when irradiation of microwave starts. Approaching 0V of secondary voltage means approaching electrical shortage status of spark plug tip electrodes. Based on this observation result, it can be found that the causal relationship between flash phenomenon and Joule heat which is generated by high-frequency big current flowing between electrodes closed to electrical shortage status.

Next, we investigate a relationship between flash phenomenon and ignition performance. **Fig. 10** shows the measurement result of the amount of radical generation derived from an oxygen atom which activates oxidation chemical reaction in ignition and combustion by spectroscopic analysis (measurement wavelength: 777.4nm). We measure spectral emission intensity of radical near spark plug only with ignition under various pressured air. The emission intensity of vertical axis is normalized by assuming spectral emission intensity of radical only with spark ignition under that pressure as 1. Horizontal axis is a pressure at ignition timing.

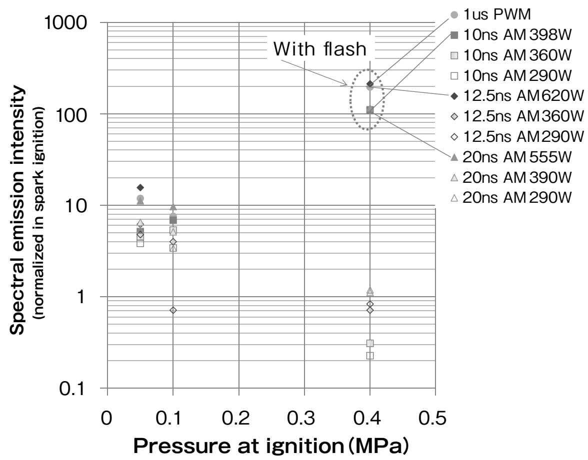

Fig. 10 Relationship between Flash Phenomenon and Spectral Emission Intensity of Oxygen Radical

Flash phenomenon happens only when both the pressure at ignition timing and microwave peak power are high. We could not find flash phenomenon under atmospheric pressure or less. In an opposite manner, under high pressure, there is no status in which the radical generates about 10 times in amount of emission compared to the case of spark ignition under atmospheric pressure, or the status the amount of emission is equal to or less than the case of spark ignition, or the status the amount of emission is more than 100 times in accordance with flash phenomenon.

Fig. 11 shows correlation between spectral emission intensity of radical and initial burning velocity (CA10: reciprocal number of 10% burning time) in constant volume chamber which is an index of ignition performance. There are two ways of initial burning velocity experiment under the pressure of 0.4MPa (about 4atmosphere) and 0.1MPa (about 1atmosphere) at ignition timing. The propane gas (C3H8) with 0.8 of the equivalent ratio is used for initial burning velocity experiment. Also, numerical data is normalized by the result of the conventional spark ignition as the reference.

There is strong correlation between spectral emission intensity of radical and initial burning velocity in both 0.1MPa and 0.4MPa. When microwave assists spark ignition, radical generation occurs under 0.1MPa air-pressure even without flash phenomenon, and initial burning velocity improves. However flash phenomenon leads to radical generation and to improvement of initial burning velocity under 0.4MPa (about 4atmosphere) which is usual pressure at ignition timing for a gasoline engine.

As mentioned earlier, in case of this plasma ignition system, in the regular use pressure area of 0.4MPa at ignition timing, “flash phenomenon” leads to “abrasion”, and “flash phenomenon” leads to “improvement of initial burning velocity”, then the difficulty of compatibility was proved through experiments.

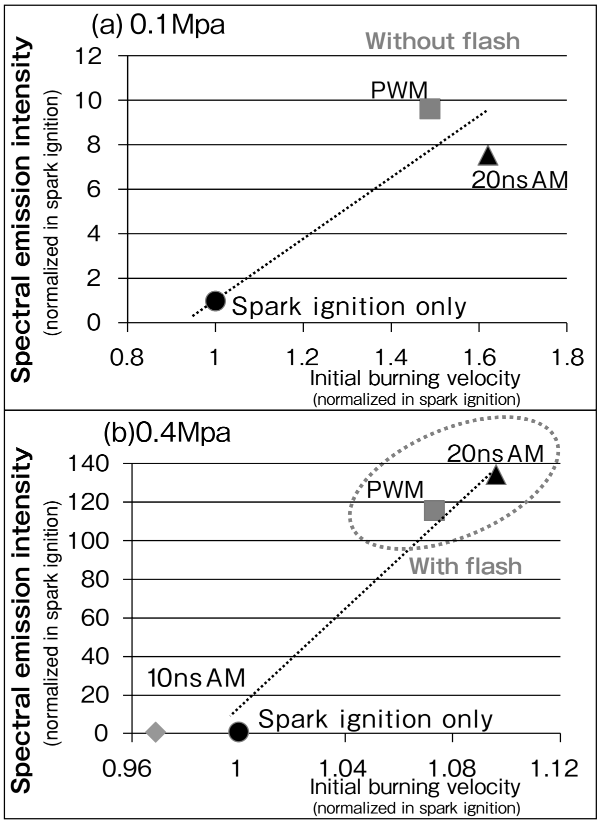

Fig. 11 Correlation between Spectral Emission Intensity of Oxygen Radical and Initial Burning Velocity

6. Mechanism

Mechanism leading up to the conclusion above can be explained as follows. Firstly, the plasma ignition system performs ignition assistance for glow discharge generated by conventional spark ignition with irradiation of high frequency (2.45GHz) electric field. Glow discharge is being maintained by plasma formed between plug electric plates, so-called streamer. The assistance of ignition energy is performed by the irradiation of high frequency electric field to this plasma.

However, in case of irradiation of high frequency electric field to plasma in general, there are two types of response cases, “collective response” and “particle response”. It is determined by whether frequency ω of irradiated high frequency electric field is greater or smaller than ω_{pe}, which is an electric plasma frequency represented by the following formula (1).

$$\omega_{pe} = \sqrt{\frac{n_e \cdot e^2}{\varepsilon_0 \cdot m_e}} \quad \text{—formula (1)}$$

n_e : Electron density in plasma (/m³)
e : Electronic charge (1.6022 × 10^{-19}C)
ε_0 : Permittivity of vacuum (8.8542 ×10^{-12}F/m)
m_e : Mass of electron (9.1094 × 10^{-31}kg)

When ω is larger than ω_{pe} , the electric field propagates in plasma and gives energy to electrons in plasma (collective response). When ω is smaller than ω_{pe} , the electric field accelerates electrons only near incidence part (particle response), and is reflected without traveling inside plasma. Thus response of high frequency electric field toward plasma is affected by an electron density of plasma.

Though the electron density of plasma in glow discharge is usually regarded as between 10^{14} and 10^{18} (m^{-3}), the electron density of plasma at 0.3MPa of ignition timing pressure was about 5.0 × 1018 (m^{-3}) in the measurement result of electron density for a spark plug tip by laser scattering measurement system in FY2013. Hence ω_{pe} , electric plasma frequency calculated by formula (1), is about 20GHz. This means that in plasma ignition system using 2.45GHz microwave, high frequency has "particle response" toward the plasma which is formed by spark ignition under regular use ignition pressure range and cannot transfer the energy into the inside thereof.

Fig. 12 schematically shows free electron existing zone near the spark plug tip during glow discharge.

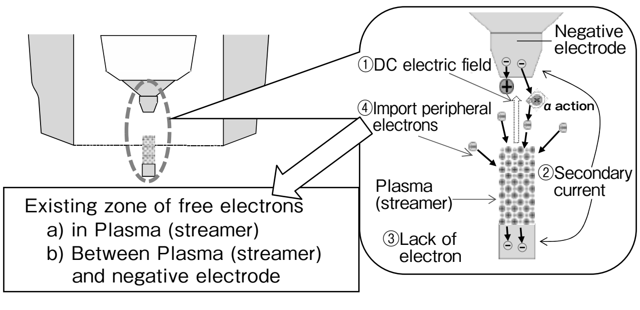

Fig. 12 Free Electron Existing Zone during Glow Discharge (Schematic diagram)

In case of sparking from ignition coil, plasma is formed at positive electrode side after the initial breakdown and subsequent arc discharge, then results in glow discharge in which comparatively low voltage is kept. At this moment, there is DC (direct current) electric field by ignition coil between plasma and negative electrode, and a little secondary current flow between positive and negative electrodes through the plasma. In order to supply secondary current, electrons in plasma flow to positive electrode, which causes the state of shortage of electrons compared to positive ions in the plasma. Then peripheral free electrons are to be incorporated in the plasma for electrical balance. Therefore, it is considered that free electron existing zone just before assisting by microwave is only a) in plasma and b) between plasma and negative electrode.

However, as electron density is high in plasma, 2.45GHz microwave electric field used for plasma ignition system is not able to work on the electrons in plasma, and works mainly free electrons existing between plasma and negative electrode.

Fig. 13 shows the state near spark plug electrode as schematic diagram from the starting of electric field irradiation of microwave, followed by generating of flash phenomenon, through mass radical production.

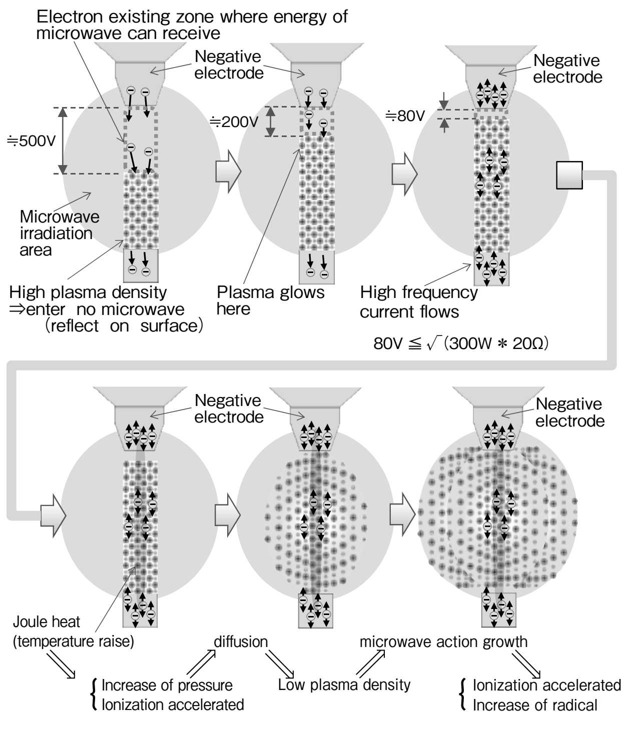

Fig. 13 Electric Field Irradiation of Microwave to Glow Discharge (Schematic diagram)

As 2.45GHz microwave electric field accelerates only free electrons existing between plasma and negative electrode because of high plasma density, plasma grows from upper edge of the plasma toward negative electrode. Plasma cannot spread into the circumferential direction because of existing of DC electric field. When a discharge voltage proportional to the gap between plasma and negative electrode drops below the level of the voltage which is calculated based on microwave output power and impedance, which causes an electrical short, and a large high frequency current starts flowing. Electrode and plasma are overheated by Joule heat caused by this current and they explosively expand. Plasma diffused by thermal expansion can supply large amount of electron, but with low electron density to microwave electric field. As a result, it is possible to generate a large amount of radical.

In this manner, it is difficult to satisfy both of improvement of ignition performance and suppression of abrasion because a combustion promotion substance, oxygen-caused radical is generated principally after thermal expansion by large high frequency current i.e. melting of electrode.

7. To Establish Compatibility between Ignition Performance and Durability Performance

As described in the previous chapter, there are three measures to establish compatibility between ignition performance and durability performance in plasma ignition system.

The first one is use of high power with high frequency which exceeds the electron plasma frequency toward high density plasma. However, as described above, numerically 20GHz is required for 0.3MPa at ignition timing, and 26GHz is required for 0.5MPa, and 37GHz is required for 1MPa. It means millimeter wave range high power (several hundred W)is needed, then the rapid development of current device technology be required.

The second one and the third one is to eliminate DC electric field. Because of exiting of DC electric field by an ignition coil, free electrons which can be acceptors to receive the energy from microwave electric field exists concentratedly only between the tips of spark plug with high density.

Therefore, the second measure is to separate off the current path of ignition coil at the same time when microwave is added.

And the third one is supply of free electrons with a certain density which can work in low frequency such as 2.45GHz etc. by realizing initial spark only with high frequency.

Among the above measures, the method of initial breakdown and supply of free electron only with high frequency is considered to be the most promising measure.

8. Conclusion

DENSO TEN have decided that it is impossible by the add-on method to the conventional ignition system to overcome the principled mechanism which disturbs to establish compatibility between ignition performance and durability performance in plasma ignition system, and to suspend the development in march 2017.

We would like to appreciate many people as well as Imagineering, Inc. for the cooperation of development activities about three and a half years.

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