5.2 Lean Limit Expansion up to Lambda 2 by Multi-Point Microwave Discharge Igniter

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Abstract

The main challenge to run the engine at ultra-lean or high EGR conditions depends on robust ignition of the mixture i.e. generation of a repeatable and robust ignition kernel to subsequently ignite the fuel-air mixture. We had developed microwave enhanced ignition system in which regular spark is augmented by microwaves which generates a bigger size plasma where. large pool of active radicals effectively increased the initial flame speed, engine efficiency, extended the lean limit and resultant decrease in COV of IMEP.

Recently, we developed another plasma-based ignition device named Microwave Discharge Igniter (MDI) which works on the principle of microwave resonation within a cavity. MDI is a compact ϕ 4.5 mm plug with a quarter coaxial cavity resonator built into its structures. It receives the microwave (MW) pulse signal at 2.45 GHz from a semiconductor-based MW generator which can be controlled to produce very precise pulse characteristics such as pulse width, pulse number and pulse frequency, with time resolution down to 0.1 μs. The MDI has been shown to have very good combustion performance, including dilution and lean limit extensions.

An igniter for gasoline engine also needs to be robust. Hence, the MDI was put under stress and endurance tests. The tests were carried out inside a constant volume chamber at non-reactive condition up to 0.5 MPa. The MDI was controlled to discharge continuously for more than 20 million times, 124-hour straight, mimicking the standard lifetime of 20,000 km highway driving.

The compact size of the igniter means that multi-point ignition inside the combustion chamber is possible. In this study, a 3-point MDI plug with M12 size was developed and tested inside a practical commercially available multi-cylinder engine to evaluate the performance of multi-point ignition. The lean limit was compared with a standard spark ignition system at 1460 rpm engine speed and 20 Nm engine torque condition. As expected, 2-point ignition performed better than single-point, reaching the air-fuel ratio of 31 (approximately Lambda, $\lambda = 2.1$) in cylinders #1 and #3. However, the variance in IMEP of cylinder #2 was higher than that of cylinder #1 and #3 at the same air-fuel ratio for both spark ignition and multi-point MDI. This is caused by cylinder difference of combustion due to the mounting platform constraint imposed on the intake manifolds. Even though the engine used for this study was not optimally designed for higher lean limits at the chosen conditions of this study, the multi-point MDI demonstrated a better load and emission performance tests maintaining exhaust gas temperatures below 300°C and achieving single digit ppm of NO compound emission.

1 Introduction

In an effort to meet demanding regulatory standards prescribed for automobiles, significant research activities have focused on reduction of emissions whiles maximizing efficiency with further downsizing of engines [1]. However, limitation on energy supply and durability concerns restrict conventional ignition systems from operating steadily at ultra-lean burn and high tumble flow/ exhaust gas recirculation (EGR) conditions [2]. Moreover, the maximum achievable EGR is constrained by misfiring and low efficiency due to the retardation effect of diluent on flame kernel growth [3]. Thus, high EGR implies high threshold energy values for successful ignition [4]. This challenge is much more pronounced for alternative fuels. Plasma-assisted ignition and combustion has been shown to extend the limits of lean burn and blowout, as well as reducing emissions and is thus, a viable alternative to conventional spark plug systems [5]-[12].

We have designed, developed and tested an ignition device termed as the Microwave Discharge Igniter (MDI), which works on the principle of microwave (MW) resonation within a quarter coaxial cavity and is capable of breakdown under high pressure conditions [5],[13]-[15]. The MDI is simple, compact in size and is resonated by a 2.45 GHz semiconductor MW oscillator which is finely tuned and controlled. Numerous oscillation patterns are achieved by varying the pulse widths, pulse periods, pulse delay, duty cycle, power per pulse as well as the number of pulses per burst, with tens of nanosecond timescale resolutions. Thus, the MDI is capable of preferential radical production: generating active radicals (O and OH for instance) that are necessary for enhancing low temperature plasma chemistry which not only enhances the plasma after breakdown, but also sustains the discharge for improved combustion performance [16]-[18]. In other words, the MW oscillation pattern affects the induced plasma characteristics, such as the ability to generate non-equilibrium, non-thermal plasmas which accelerates the growth of flame kernel and thereby reducing misfiring at ultra-lean conditions [19]-[22].

Our previous studies conducted in constant volume combustion chambers with optical diagnostics showed that the single point MDI outperforms the conventional spark plug ignition system [14],[23]. Multi-point ignition has been shown to maximize ignition volume, enhance flame development and growth, which in turn increases lean burn limits and dilution rates [24]-[26]. In this study, we demonstrate the capability of an M12, 3-point MDI (each port has a ϕ 4.5 mm plug) to extend the lean burn limit up to Lambda, λ of 2.1, whiles exhibiting comparatively better emission performance. The compactness of this MDI makes it a flexible device amenable to various designs and configurations of combustion chambers with different engine heads. The multi-point MDI was applied to a multi-cylinder commercially available engine and its ignition performance evaluated and compared to a conventional spark plug ignition system at an engine speed of 1460 rpm and a torque of 20 Nm.

2 Experimental Setup

2.1 Microwave Oscillation and Control

The MW oscillation is performed by a semiconductor device which permits varying degrees of oscillation patterns. As shown in figure 1, oscillation patterns with equal pulse

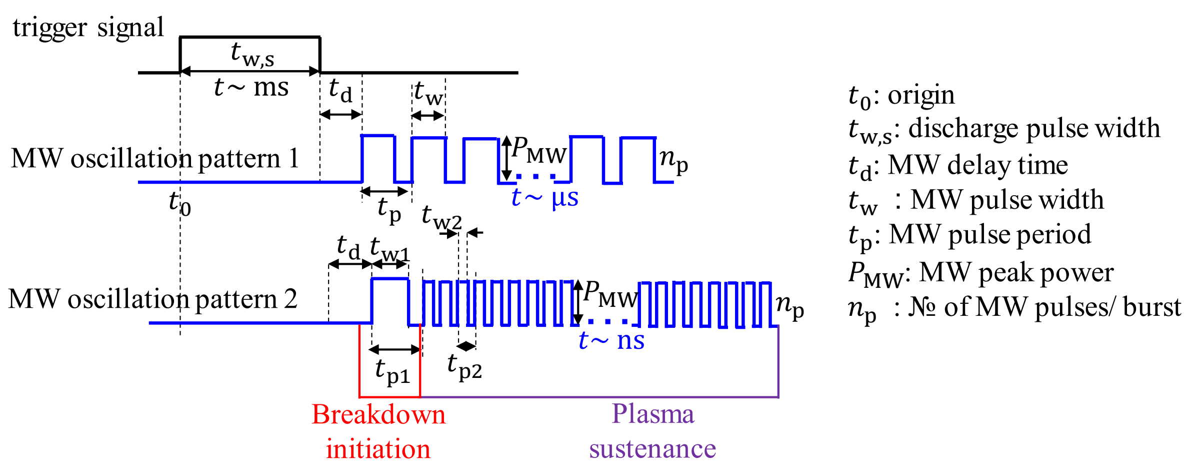

Figure 1: Pictorial representation of MW oscillation pattern and its trigger signal

widths t_w, and equal pulse periods t_p, are possible and labelled as pattern 1. In addition pattern 2 which has different timescales for set 1 (t_{w1}, t_{p1}) and set 2 (t_{w2}, t_{p2}), is attainable and is the most applied pulse train for our MW-enhanced plasma-assisted combustion [13]-[15],[23]. The MW oscillation pattern permits the spatial and temporal control of both the growth and lifetime of the induced plasma which in effect influences the production of active radicals for combustion. The timescales for these oscillation patterns are available from microseconds to nanoseconds levels per pulse at MW output power P_{MW}, of tens of watts to kW level per pulse, achieving several hundreds of millijoules per pulse. The number of pulses per burst n_p, could be varied up to 2400.

The equivalent electric circuit for a single cavity as well as pictures of the 3-point MDI used in this study are shown respectively in figure 2 (a) and figure 2 (b) [15]. Figure 2 (b) also shows the MW-enhanced plasma during the MDI discharge.

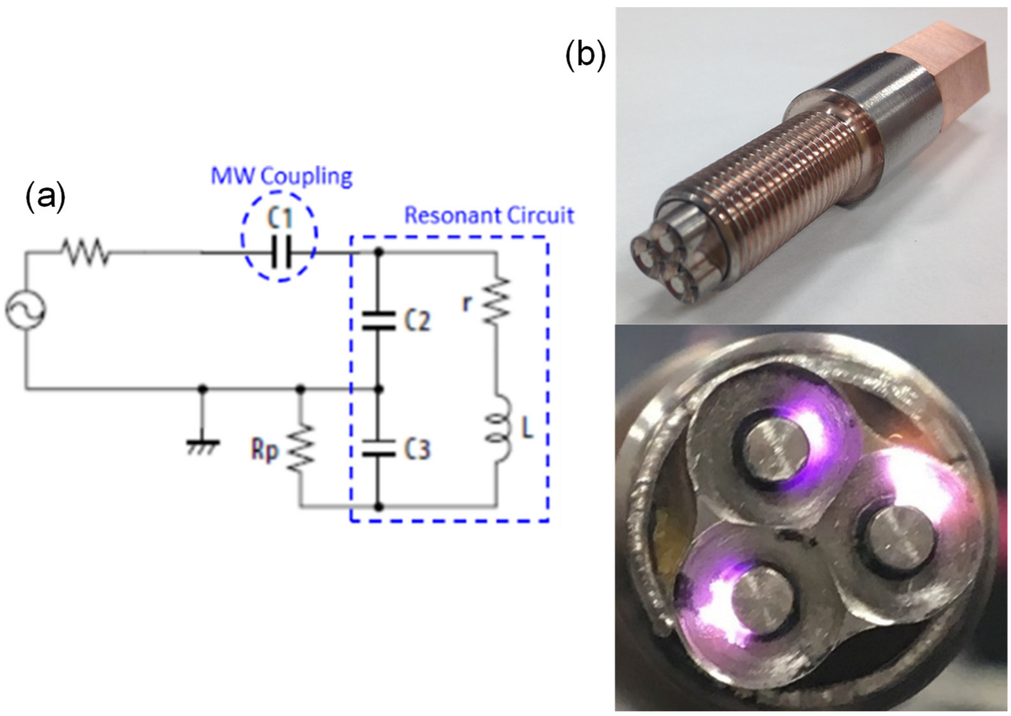

Figure 2: Equivalent electric circuit of a single cavity (a) and pictures of the M12, 3-point MDI used in the experiment (b)

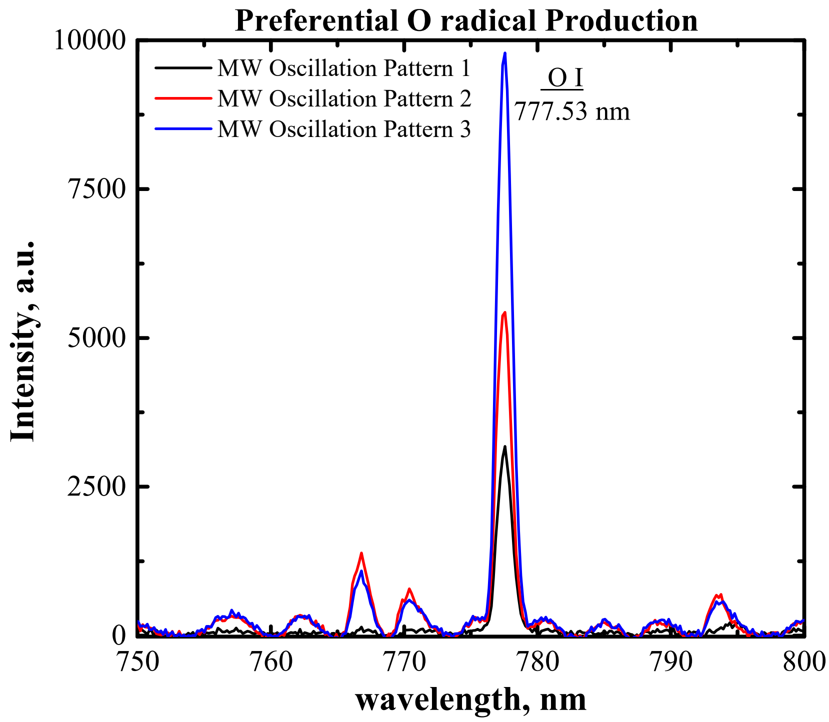

Figure 3: The effect of MW oscillation pattern on O radical production

Each of the ports within the 3-point MDI are separately controlled by three similar MW oscillators. Thus, the MDI could be operated as a single to a 3-port discharge device. This further enhances the capacity to preferentially generate radicals such as oxidizers in high concentration levels for efficient combustion. In past studies, we have shown how these patterns of oscillation can influence the generation of preferred radicals. For instance, figure 3 shows the O radical spectral intensity variations obtained as a result of different MW oscillation patterns. Table 1 describes the parametric values of the oscillation patterns used in figure 3. E_{MW} is the MW input energy per total period.

More so, shown in figure 4 [23] is the effect of oscillation pattern per pulse on plasma characteristics. Longer t_{w} are required to initiate breakdown and thus it is shown in the figure that, the first pulse spectra have a lot of atomic lines coming from the erosion of electrode and antenna material. Subsequent pulses are short pulsed and thus minimize erosion whiles generating molecular spectra. Figure 5 shows the effect of oscillation pattern on O radical production using the Taguchi Method [13]. O radical is an intermediate species during flame development and growth, and thus knowing the oscillation patterns that influence its production is important. It is observed in the figure that, the parameters that had a positive effect (high signal-to-noise ratio) on O radical production were the number of pulses per burst n_{p2}, and pulse period t_{p2}, for set 2 pulses. These are shaded green in figure 5.

Table 1: MW oscillation used for O radical generation shown in figure 3

Pattern №	MW Oscillation Pattern			
	t_{p2}, ms	t_{w2}, ms	n_{p2}	E_{MW}, mJ
1	2	0.1	1400	232
2	2	0.3	700	344
3	2	0.2	1400	456

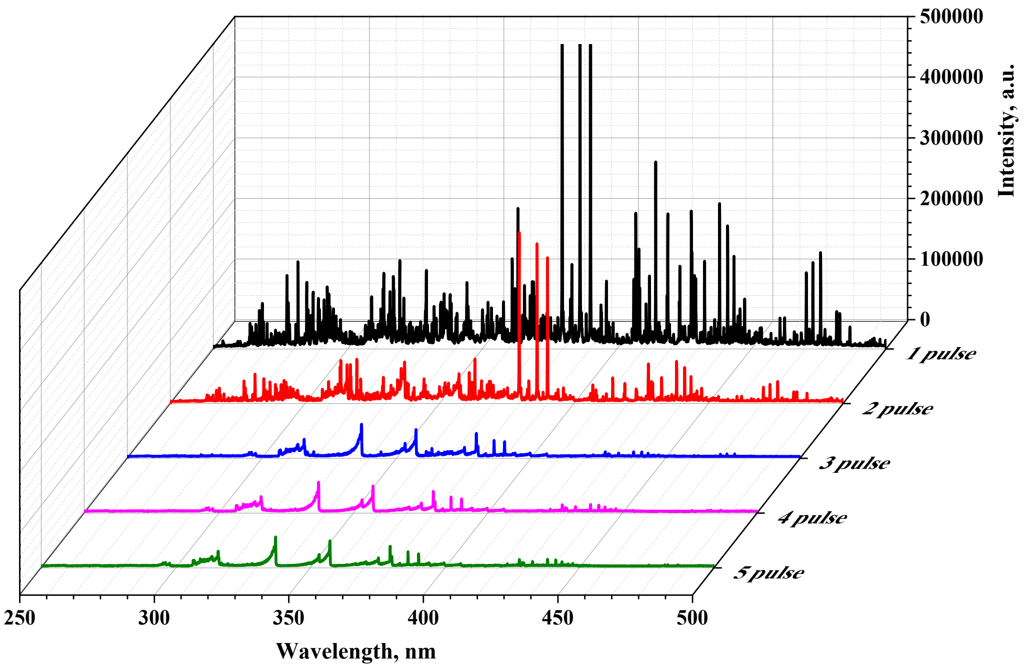

Figure 4: The effect of MW oscillation pattern variation per pulse on plasma characteristics

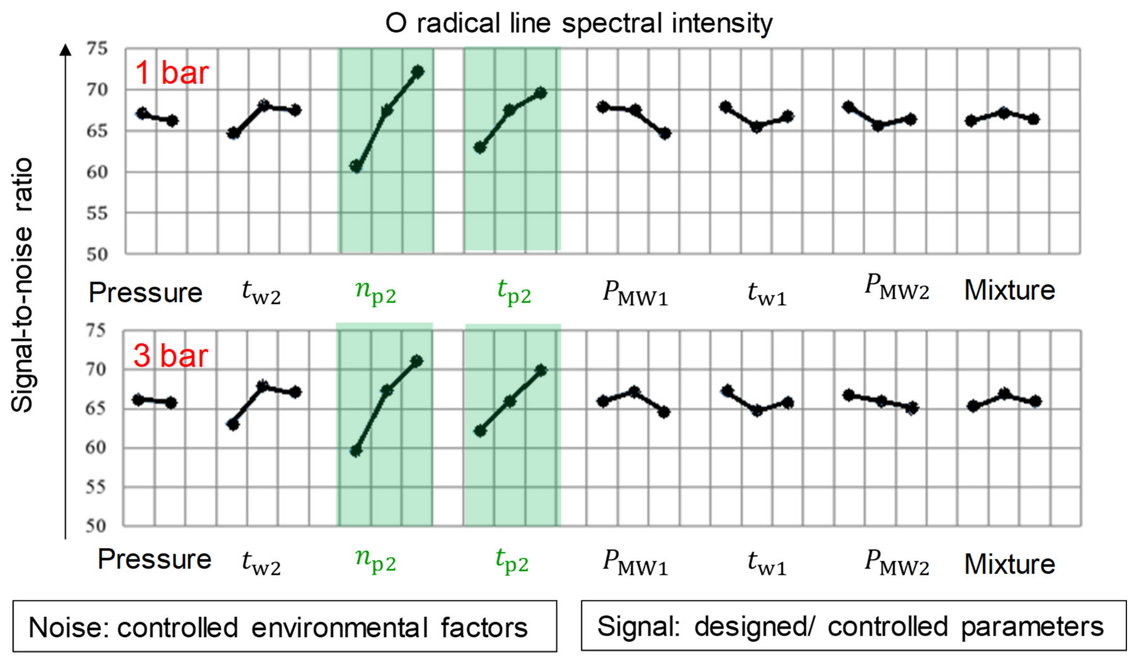

Figure 5: The effect of MW oscillation pattern on O radical production using Taguchi method

2.2 Constant Volume Combustion Chamber

In previous studies [13],[15], stress and endurance tests of the single MDI were performed in a constant volume combustion chamber. The single MDI device was test-ran continuously for 10 hours at wide-open-throttle load condition and then also continuously for 100 hours at IMEP of 550 kPa part load condition. Both test-runs were conducted at engine speeds of 3000 rpm. Under these test conditions, the MDI was

Table 2: Experiment conditions of the stress test in the constant volume chamber

Parameter	Condition
№ of discharges	Over 20 million times
Frequency of discharge	50Hz (equivalent to ignition interval of 6000rpm)
Gas	N2 (non-reactive, no oxidation)
Pressure	0.5 MPa
Flow rate	< 1000 mL/min (for gas exchange)

robust, flexible and also outperformed the conventional spark ignition system. The constant volume chamber used for previous as well as for this study, is a pent-roof type with a capacity of 185 cc and is supplied with propane-air mixture from a pre-mixing tank. The temperature of both the chamber and its contents were set at 298 K during the test-runs. The MDI is installed in the center of the pent-roof and the chamber is equipped with a piezo-electric transducer (Kistler 6052 C) for pressure measurements.

The stress tests were performed in a non-reactive medium with pressure of 0.5 Mpa. The MDI discharge was carried out continuously for 124 hours, over 20 million discharge times replicating an equivalence of the standard lifetime of 20,000 km high-way driving. The experimental conditions at which the stress tests were performed are as shown in table 2. These tests led to the erosion of electrode material as well deposition of substances on the MDI outer parts. The erosion and deposition have the potential to restructure the MDI's geometry and thus affects its resonance performance. Pictures of the MDI before, during and after the stress tests are shown in figure 6 [15].

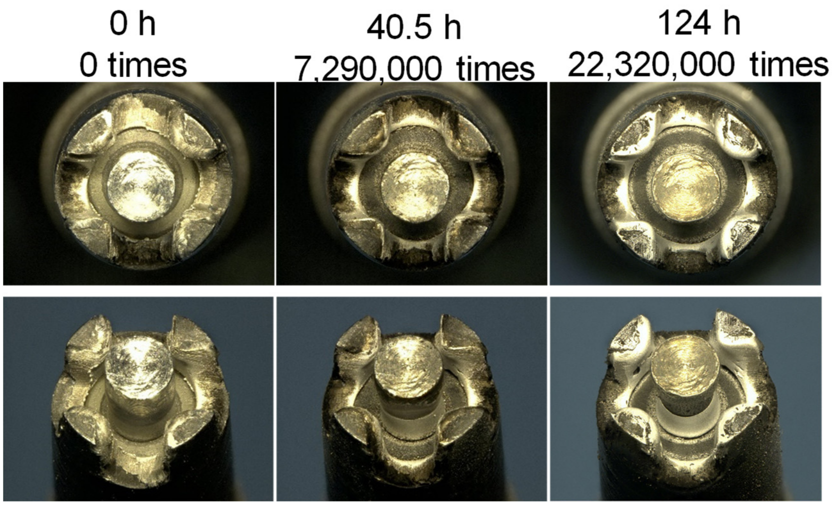

Figure 6: Pictures of the single MDI prototype before and after stress tests in a constant volume chamber (top: front view, bottom: tilted angle view)

The semiconductor MW oscillator was capable of self-correction and re-adjusting to a new resonant frequency to ensure successful ignition and preventing misfiring. The self-adjusted resonant frequencies were measured by an RF vector network analyzer and are shown in figure 7. This implies that not only is the MDI able to withstand tens of millions of discharge times, but also the MW oscillator induces the waves at frequencies that ensure efficient coupling with the plasma allowing high combustion efficiency.

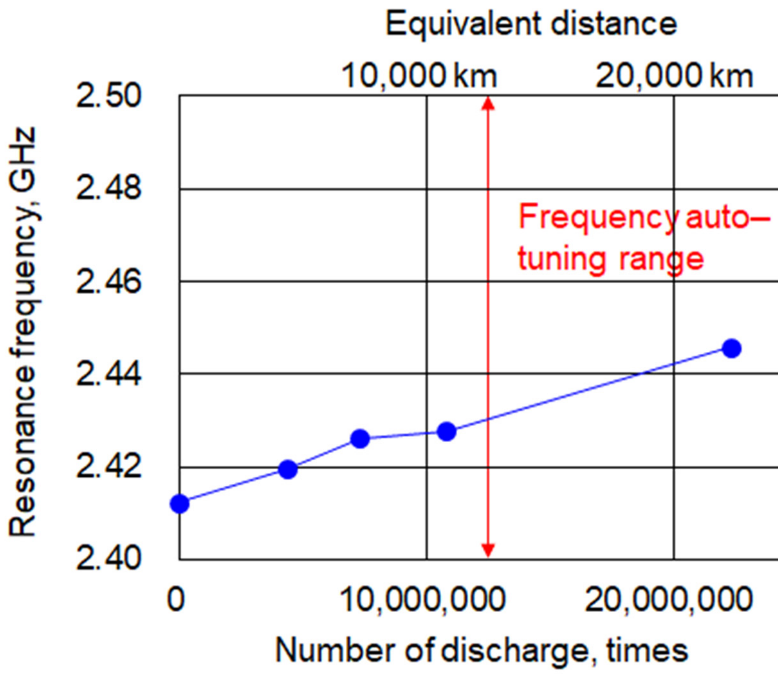

Figure 7: Auto frequency adjustment during the stress test in a constant volume chamber

2.3 Multi-cylinder Production Engine

The specification of the multi-cylinder engine used in this study is given in table 3. The engine is a three-cylinder Daihatsu KF-VE5 naturally aspirated engine with a port-fuel-injection system for the intake. The dimensions of the engine are a bore and a stroke of 63 mm and 70.4 mm respectively, with a total displacement of 658 cc. The engine was not optimally designed for higher lean limits and dilution rates. Hence, all tests performed were conducted at an engine speed of 1460 rpm and a torque of 20 Nm. Data recording was done by a standard data logging system provided by Daihatsu.

Previous results [15] demonstrate that the multi-point MDI outperformed the spark ignition system in all the three cylinders of the production engine. Furthermore, the 2-point experimented MDI exhibited better performance when compared with the single-point experimented MDI, attaining the air-fuel ratio (AFR) of 31.

Table 3: Specifications and operating conditions of the multi-cylinder engine

Parameter	Specification
№ of cylinders	3
Engine model	KF-VE5
Displacement	658 cc
Compression ratio	12.2
Bore x Stroke, mm	63 x 70.4
Fuel injection	PFI
Engine speed	1460 rpm
Torque	20 Nm
EGR rate	0
Excess air ratio	>2.1

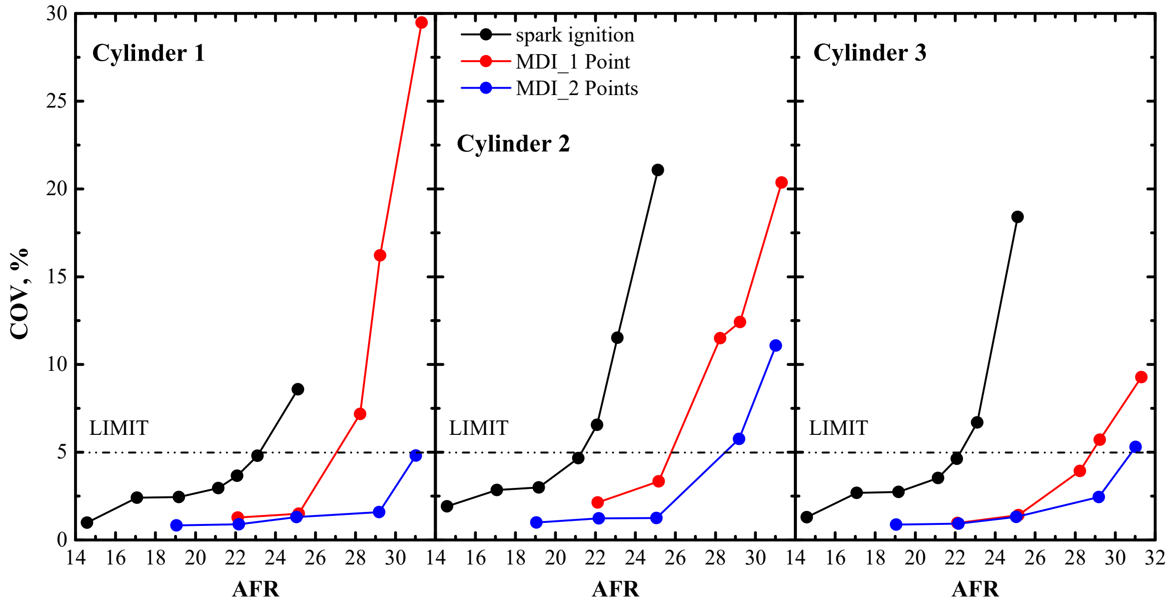

Figure 8: Performance comparison of spark plug and 1/ 2-point MDI in multi-cylinder engine

Even though the engine was not optimally designed for higher lean limits at the experimented low speed and low torque conditions, multi-point MDI demonstrated a better performance when compared with conventional spark ignition systems. The coefficient of variation (COV) for cylinder 2 was the largest under all cases and conditions of study. This is caused by cylinder difference of combustion due to the mounting platform constraint imposed on the intake manifolds. Figure 8 shows the performance comparisons of the ignition systems studied [15].

3 Results and Discussion

3.1 Load Performance Test of Lean Burn

Figure 9 show the variations of the IMEP with CA during the flame development time, that is, between discharge initiation and 10% of cumulative net heat release. The IMEP variations shown are for a 300-cycle test-runs each, for selected AFRs up to the limiting conditions respectively for the spark, 1- and 2-point MDI ignition systems. The lean limit expansion performance is shown only for cylinder 1 of the multi-cylinder engine. We observe that at leaner conditions, long initial combustion period generates low IMEP cycle. The conventional spark ignition system is unstable at AFR of 25; whiles the 1-point MDI becomes unstable beyond AFR of 25. The 2-point MDI performed comparatively better at AFR of 31, emphasizing the significance of the multi-point MDI for enhancing the efficiency of combustion with microwaves.

3.2 Emission Performance Test of Lean Burn

Figures 10 – 12 show the exhaust gas temperatures (before catalyst), the total hydrocarbon (THC) and NO emissions respectively for all the ignition systems studied. Here also, the graphs shown are the performance of cylinder 1 of the multi-cylinder engine. In the case of the exhaust gas temperature, the MDI outperformed the standard spark ignition system, exhausting at relatively low temperatures at comparatively high AFR

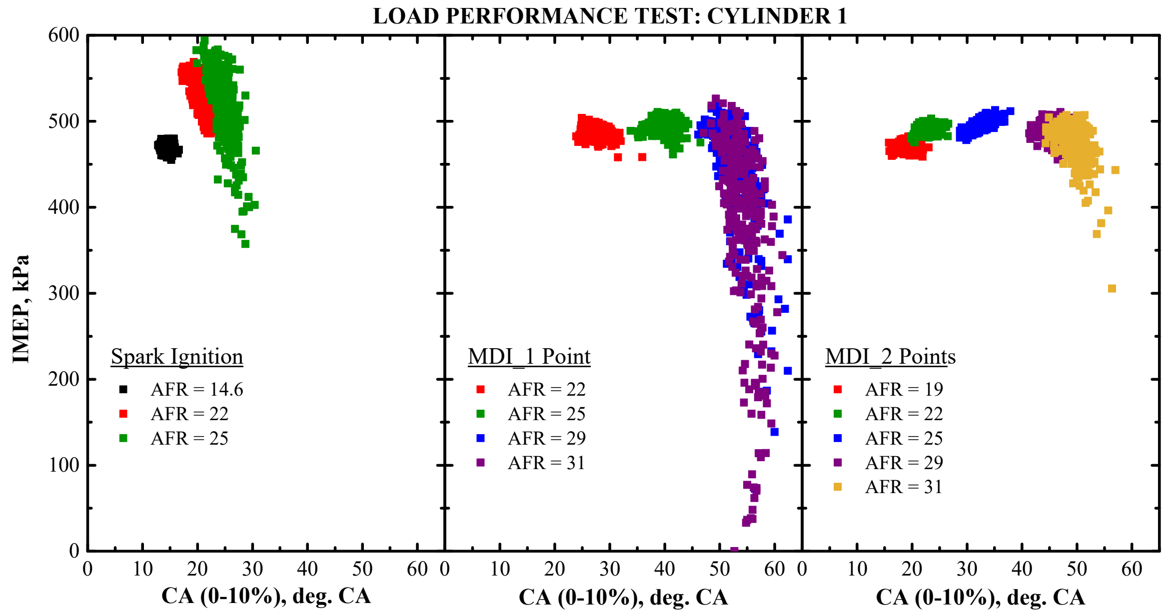

Figure 9: IMEP variation as a function of CA during flame development time for the ignition systems studied

values. Specifically, the multi-point MDI was able to maintain exhaust gas temperatures below 300°C at an AFR value of 31. Moreover, the THC emission of 2-point MDI was the minimum at lean burn conditions. The NO emissions were the highest for 2-point MDI within AFR values of 20 – 25. The multi-point MDI emits single digit ppm of NO compounds at the AFR values of 30 and 31. This makes the MW-assisted combustion a robust and an efficient system compared to combustion via conventional spark ignition. Thus, the multi-point MDI is capable of generating non-equilibrium plasma with active radicals that enhances the combustion process.

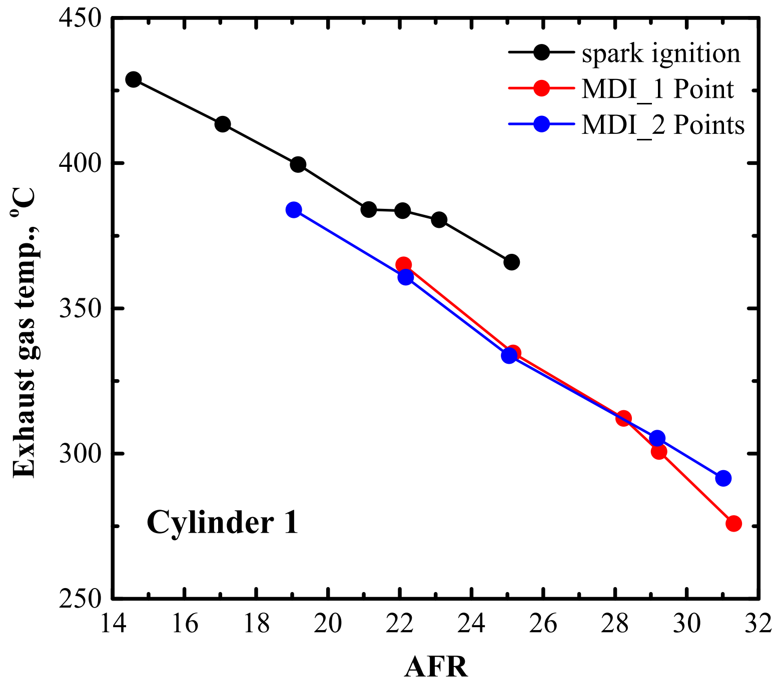

Figure 10: Exhaust gas temperature as a function of AFR for the ignition systems studied

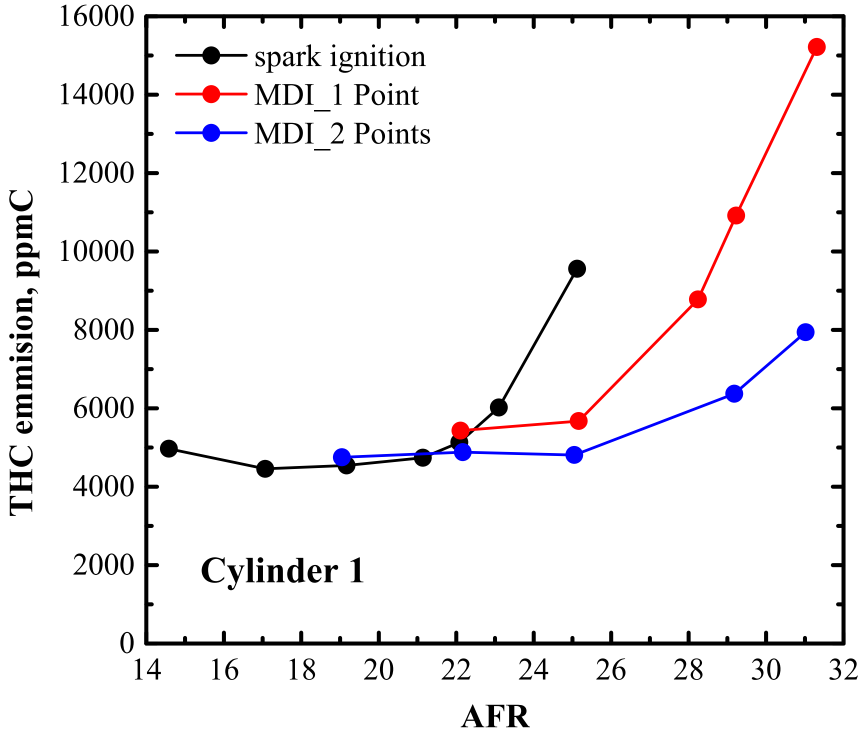

Figure 11: Total hydrocarbon emission as a function of AFR for the ignition systems studied

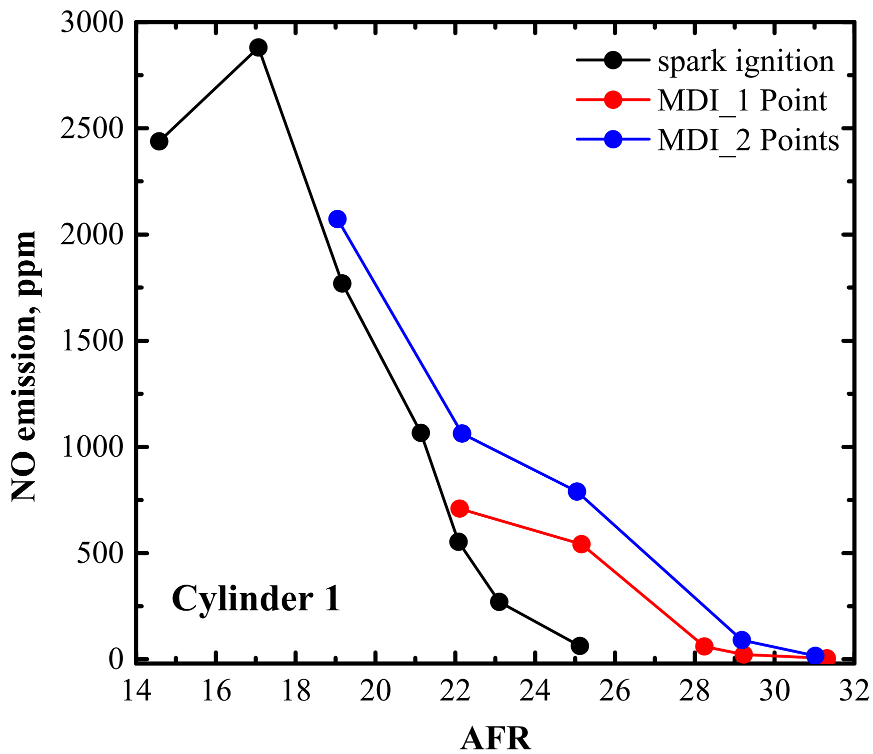

Figure 12: Nitrogen oxide emission as a function of AFR for the ignition systems studied

4 Conclusion

In this study, the essence of MW oscillation pattern for enhancing combustion efficiency was emphasized by comparing the performance of a multi-point MDI to that of a conventional spark ignition system. First, we observed that despite the erosion and deposition effect on cavity structure, the semiconductor MW oscillator is capable of auto-adjusting mechanism, attaining new resonant frequencies for improving combustion efficiency. Thus, the multi-point MDI generated selective active radicals that enhances low temperature plasma chemistry.

Second, considering the test-runs performed on the commercially available multi-cylinder engine (by Daihatsu Motors), the multi-point MDI exhibited a better COV of IMEP performance compared to the conventional spark ignition system. The multi-point MDI extended the lean limit expansion to an AFR of 31 (i.e. λ of 2.1) showing a comparatively better performance than that of the 1-point MDI and spark ignition. Thus, MW coupling for increased combustion efficiency is demonstrably possible with the multi-point MDI device in practical automobile engines.

Third, at higher lean burn limits, the multi-point MDI maintained exhaust gas temperatures below 300°C, and achieved lower THC and NO emissions. Thus, the multi-point MDI would be able to realize the stringent emission regulatory standards for automobiles whiles enhancing the combustion efficiency of the engines.

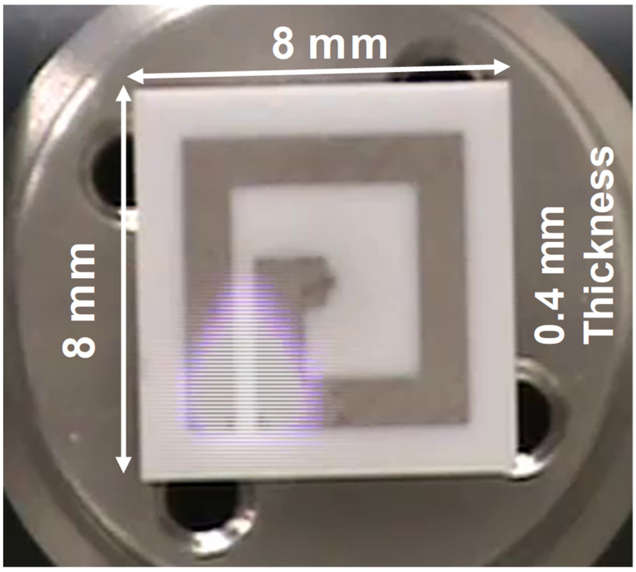

Figure 13: Miniaturized flat-panel plasma igniter with MW-sustained discharge

5 Future Work: A Novel Plasma Igniter [27]

We have developed, tested and currently improving on the design of a miniaturized novel igniter termed as the Flat-Panel Plasma Igniter (FPI). The FPI is an 8 mm × 8 mm × 0.4 mm ceramic panel with conductive inlay for microwave resonation. The image of the FPI with MW-sustained discharge are as shown in figure 13. We have in a previous study examined the performance of the FPI in a constant volume chamber with propane-air mixture where successful ignition was achieved at an equivalence ratio of 0.6. The FPI's size is a characteristic advantage for various geometries of combustion chambers. We hope that this device would revolutionize the automobile industry and the drive to achieve reduced emissions with highly efficient combustion engines.

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