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# Flame Analysis of Combustion Pressure Characteristics on the Conventional Point Sparks and Arc Plasma Discharges for GDI

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**Abstract:** This study performed an experimental analysis on plasma ignition performance to overcome the problem of unstable combustion and miss fire by applying arc plasma discharges which replicates the static combustion system of a gasoline engine. The experimental device was a static combustion chamber having a capacity of 450 cc which is 50 cc larger than that of a gasoline direct injection engine (1,600 cc/4 cylinder), so as to allow the visualization of combustion flames. Consequently, the arc plasma discharges averagely had a faster combustion response than point sparks by 1ms and they also achieved an improved combustion pressure by 3 bar than that of point sparks. Therefore, this experiment could be found to generate the similar performance such as combustion pressure which is obtainable from point spark, even under lean combustion conditions.

**Key words:** New combustion, point spark, arc plasma, fuel efficiency, combustion flame, unstable combustion

## INTRODUCTION

New combustion technology for gasoline engines is often mentioned as another technique which may extremely improve the combustion's performance as replacement from point ignition to plasma instead of the conventional characteristics (Raunmiagi and Bielawski, 2014; Kim and Choi, 2016).

New combustion which is known to significantly improve the stability of combustion and fuel efficiency, offers the advantage of maximizing the energy of sparks by delivering the plasma source to between the plug electrodes, even under lean conditions (Tsai, 2012; Kim *et al*., 2015).

Ignition technology which is the key to delivering energy in a gasoline engine is essential to generate sparks between the ignition plug electrodes using electronic control (Kim *et al*., 2016). However, new combustion technology is needed because the existing low-voltage point ignition systems tend to cause unstable combustion (Pastor *et al*., 2016; Prasad *et al*., 2016). This is because the use of turbo chargers maximizes swirls and tumbles in combustion chambers (Starikovskiy and Aleksandrov, 2013). To resolve this issue, previous research employed plasma technology involving microwaves, lasers and coronas but higher costs arising from the use of additional devices have prevented their widespread applications to gasoline engines (Kim and Choi, 2015). While many studies have used plasma to stabilize or improve combustion performance, most are based on simulations (electromagnetics, combustion analysis, structural analysis) because of issues relating to investment costs or production (Nedanovska *et al*., 2015).

Against this backdrop, this study analyzed the characteristics of combustion pressure and flames using arc plasma discharges to resolve the issue of unstable combustion and fires occurring in the combustion chamber of gasoline engines. An experiment was also conducted to derive measures for an improved combustion performance.

## MATERIALS AND METHODS

**Experimental devices and methods:** Figure 1 shows the schematic diagram of the experimental devices and flame visualization with conventional point sparks and arc plasma discharges.

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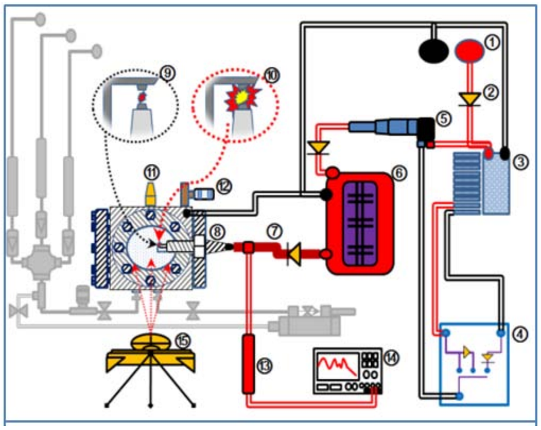

Fig. 1: Schematic diagram of experimental devices and flame visualization with the conventional point sparks and arc plasma discharges; 1) Power supply; 2) Diodes; 3) DAQ hardware; 4) IRFP or IGBT; 5) Spark or plasma coil; 6) Arc plasma generator; 7) H/V cable; 8) Plasma or spark plug; 9) Point spark; 10) Arc plasma discharge; 11) Oxygen sensor; 12) Pressure sensor; 13) H/V probe; 14) Oscilloscope and 15) H/S camera

flames. A pencil-type ignition coil was used to minimize energy loss. An Insulated Gate Bipolar Transistor (IGBT) and low resistor field effect processing transistor (IRFP) were employed as transistors to generate spark and plasma sources. Lambda values (air fuel ratio) were assigned to allow for the monitoring of the air fuel ratio using an oxygen sensor. The circuit for arc plasma discharges was designed to deliver a high voltage energy of 25 kV or higher to the spark plug. The air fuel ratio was controlled to mix air and fuel ($C_3H_8$) using a control algorithm after communicating the output signal of the Mass Flow Controller (MFC) to Labview. The combustion pressure was monitored to detect minimum or maximum pressure by installing a sensor within the static combustion chamber.

Using the static flame software to determine the air fuel ratio, point sparks and arc plasma discharges were generated under constant pressure conditions in the flame visualization chamber. A high-speed camera was used to extract flames for both the point sparks and arc plasma discharges in Frames Per Second (FPS) at 1ms resolution. The experiment was conducted such that both point sparks and arc plasma discharges were generated at 1 msec with the two ignition sources having the same contact timing. Table 1 gives the specifications of the static flame system for point sparks and arc plasma discharges while Table 2 shows the experimental conditions for point sparks and arc plasma discharges.

Table 1: Specifications of a static flame system for point sparks and arc plasma discharges

| Items | Specifications |
|---|---|
| Pressure sensors | 0-160 bar |
| Mass flow controller | 0-1.5 L/m |
| Flame chamber | 450 cc |
| Oscilloscope | 70 MHz |
| Capacitor | 25 kV (2 way) |
| Ignition coil | 15-25 kV |
| Spark plug | Iridium |
| Plasma plug | Nickel |
| H/V probe | 500:1 |

Table 2: Experimental conditions for the conventional point sparks and arc plasma discharge

| Items | Specifications |
|---|---|
| Air fuel ratio ($\lambda$) | 1.0, 1.2, 1.4 and 1.6 |
| Initial pressure | Fixed 4.5 bar |
| Fuels | Air and $C_3H_8$ |
| Ignition types | Point and arc plasma |
| Plug gap of point and plasma | 1.0 mm |
| Experimental repeat | 5 times |

## RESULTS AND DISCUSSION

Figure 2 shows the results of flames from conventional point sparks and arc plasma discharges when $\lambda = 1.0$ (air fuel ratio = 15.5:1). The time of detected flames was presented from 0 msec at the first occurrence of point sparks and arc plasma discharges up to 45 msec the point at which combustion is complete.

At 0 msec, the point sparks showed a small dot. From 0-40 msec, the pressure layer spread gradually. From 45 msec onwards, the combustion flames spread. At 40 msec, the combustion flames spread from between the spark plug's electrodes to the center of the nucleus.

As for arc plasma discharges at 0 msec, the stronger energy characteristics resulted in an enhanced volume with maximized plasma. From 0-35 msec, they showed a faster response by 5 msec than the point sparks. The combustion flames at 35 msec had a more active flame nucleus than that of point sparks at 40 msec. The combustion process had already stabilized at 40 msec and the maximum pressure and combustion characteristics with spread flames were observed at 45 msec. The faster response can be attributed to the high voltage characteristics of the arc plasma discharges activating the free electron state at $\lambda = 1$ and maximizing the nucleus.

Figure 3 shows the results of flames from the conventional point sparks and arc plasma discharges when $\lambda = 1.2$. The time of detected flames was present from 0 msec at the first occurrence of point sparks and arc plasma discharges up to 55 msec, the point at which combustion is complete. For point sparks, the spreading of the pressure layer was shown from 0-35 msec and a greater delay was observed compared to the results

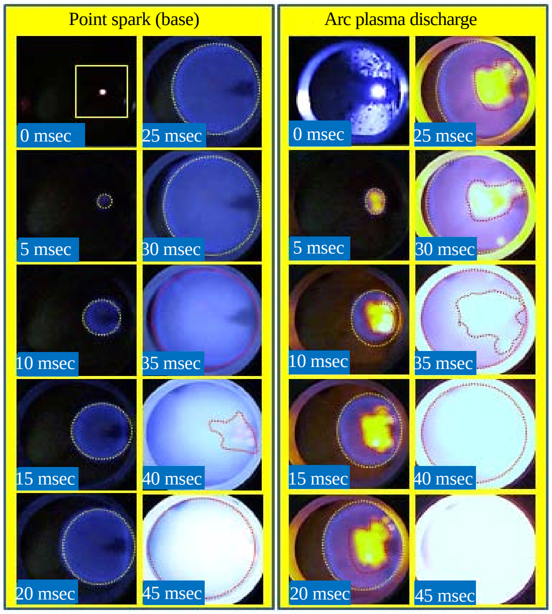

Fig. 2: Analysis results of flames from the conventional point sparks and arc plasma discharges at lambda 1.0 with a static combustion chamber

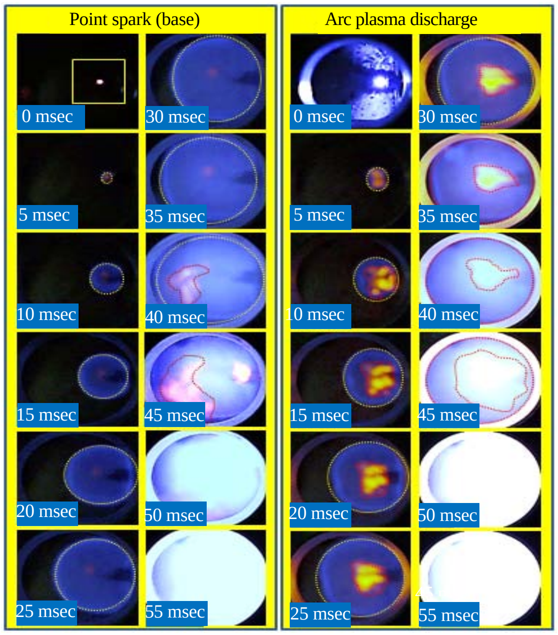

Fig. 3: Analysis results of flames from the conventional point sparks and arc plasma discharges at lambda 1.2 with a static combustion chamber

for λ = 1.0. From 5-35 msec, there was some spreading of the residual flames. The combustion flames in the pressure layer failed to completely reach the chamber walls at 40 msec but succeeded at 45 msec.

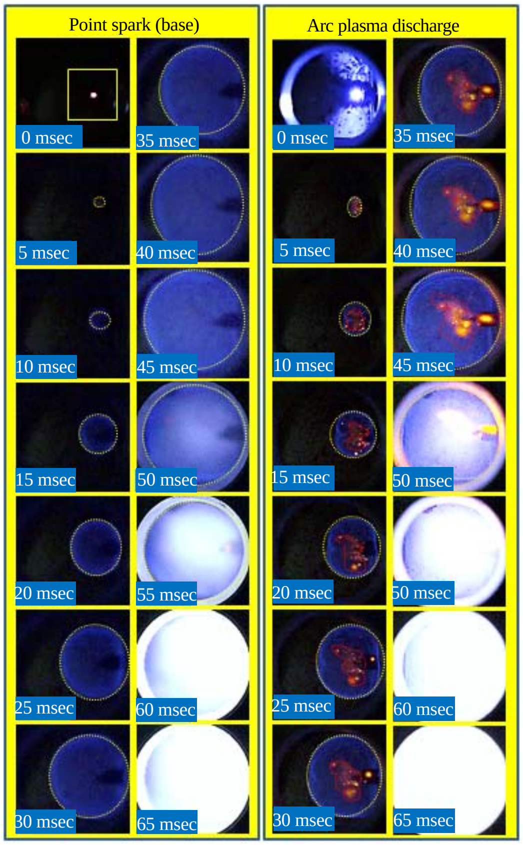

Fig. 4: Analysis results of flames from the conventional point sparks and arc plasma discharges at lambda 1.4 with a static combustion chamber

For arc plasma discharges, the distance between the chamber walls and pressure layer grew significantly closer from 0-35 msec. At 40 msec, the initial characteristics of the flames had already grown active and the nucleus spread from the nucleus to the chamber walls.

This can be attributed to the delayed spreading of the pressure layer arising from the leaner mixture at λ = 1.2 than λ = 1.0. The faster response by 5 msec was achieved by the stronger current in the arc plasma discharges than in the point sparks.

Figure 4 shows the results of flames from the conventional point sparks and arc plasma discharges when λ = 1.4. The time of the detected flames was present from 0 msec at the first occurrence of point sparks and arc plasma discharges up to 65 msec, the point at which combustion is complete.

For the point sparks, the spreading of the pressure layer was present from 0-45 msec and a greater delay was observed compared to the results for λ = 1.2. From 50-55 msec, the active flames were converted into fuel. From 60-65 msec, a stable combustion was observed before gradual dissipation.

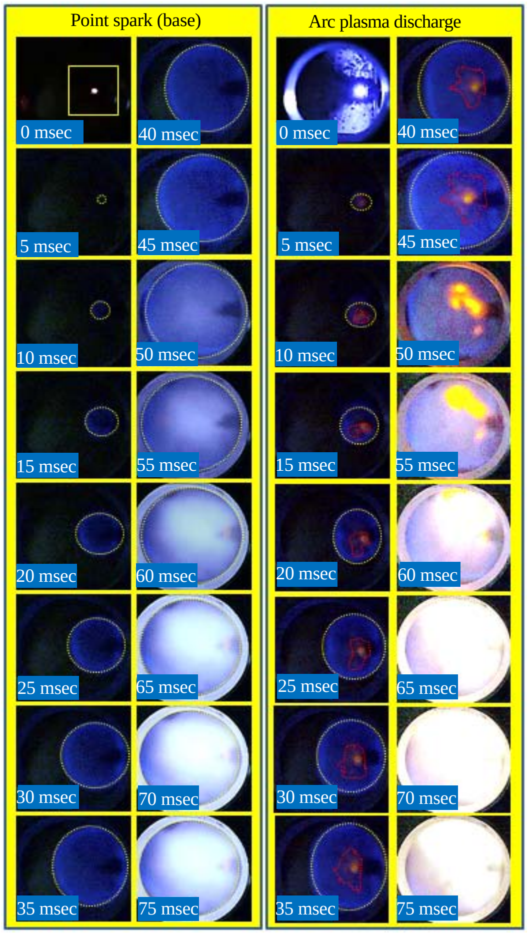

Fig. 5: Analysis results of flames from the conventional point sparks and arc plasma discharges at lambda 1.6 with a static combustion chambe

For the arc plasma discharges, from 0-45 msec, the residual flames and nucleus were maintained within the pressure layer while spreading to the chamber walls. Unlike the point sparks, all of the flames generated nuclei and gradually spread to the chamber walls. From 45-50 msec, the flames gradually became active and were converted into fuel. From 55-60 msec, stable combustion was observed before gradual dissipation. The response rate of the arc plasma discharges and initial combustion were faster than that of the point sparks by 5 msec.

This can be attributed to the pressure layer's delayed spreading caused by the leaner mixture at λ = 1.4 than at λ = 1.2 and the maximized energy of nuclei found in the arc plasma discharges.

Figure 5 shows the results of flames from the conventional point sparks and arc plasma discharges when λ = 1.6. The time of detected flames was present from 0 msec at the first occurrence of point sparks and arc plasma discharges up to 75 msec, the point at which combustion is complete.

For the point sparks, the spreading of the pressure layer was present from 0-50 msec and a greater delay was observed compared to the results for λ = 1.4. From 55-65 msec, the flames were some what delayed before combustion. From 7-75 msec, the flames gradually dissipated and failed to reach the chamber walls.

The arc plasma discharges exhibited a greater delay in combustion compared to the results at λ = 1.4. From 0-45 msec, there was a gradual spreading of the weak residual flames within the pressure layer. From 50-55 msec, the residual flames intensified and spread further. From 60-65 msec, the pressure layer and flames reached the chamber walls. From 70-75 msec, stable combustion was observed before gradual dissipation. The response rate of combustion was 5-10 msec faster than that of the point sparks.

This is because of the leaner mixture at λ = 1.6 than λ = 1.4 which caused a greater delay in the spreading of the pressure layer. Since, the volume of arc plasma discharges was larger than that of the point sparks, the flames were able to reach the chamber walls, even at λ = 1.6. Arc plasma discharges generate energy at a high voltage, thus achieving improved response rates and stronger flames compared to point sparks, even under lean conditions.

Figure 6 shows the results of combustion pressure in relation to the point sparks and arc plasma discharge when λ = 1.0, 1.2, 1.4 and 1.6 in a static combustion chamber. An analysis of the response rate and maximum combustion pressure of the point sparks showed that combustion pressure decreased and time delay increased with λ in the order of λ = 1.0>1.2>1.4>1.6.

On the other hand, the response rate and maximum combustion pressure of the arc plasma discharges gradually decreased in the order of λ = 1.0>1.2>1.4>1.6. The results for the arc plasma discharges were higher for the point sparks at all λ values. In addition, the response of the arc plasma discharges was 5-10 msec faster than that of the point sparks at λ = 1.0, 1.2, 1.4, 1.6 resulting in a higher pressure by 3 bar on average. The higher pressure can be attributed to the initial ignition source at the arc plasma discharges having a larger volume and being stronger than that of the point sparks.

The time to reach the walls of the combustion chamber in the spreading process of the combustion's pressure layer was found to be the same as the time of detection by the combustion pressure sensor. If the point sparks used by a combustion engine are replaced with arc

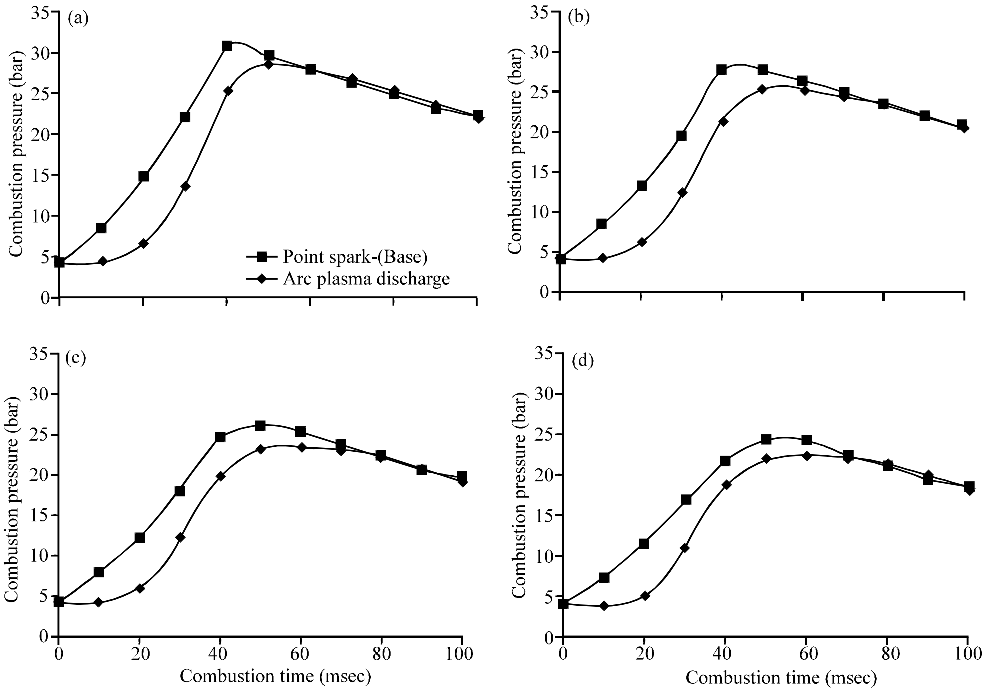

Fig. 6: Results of combustion pressure from lambda 1.0-1.6 with the conventional point sparks and arc plasma discharges with a static combustion chamber; a) Combustion pressure of λ = 1.0; b) Combustion pressure of λ = 1.2; c) Combustion pressure of λ = 1.4 and d) Combustion pressure of λ = 1.6

plasma discharges we can expect an improvement in fuel efficiency and output as well as a reduced emission of harmful gases.

## CONCLUSION

This study analyzed the characteristics of the combustion pressure and flames by using arc plasma discharges to resolve the problems of unstable combustion and fires. The following conclusions were derived:

- When the arc plasma discharges were used instead of point sparks from 0-35 msec at λ = 1.0, the response rate improved by 5 msec
- Arc plasma discharges already activated initial combustion characteristics at λ = 1.2 and the nucleus spread from the center to the chamber walls
- Even when the arc plasma discharges were under extremely lean conditions at λ = 1.4, they generated flames while maintaining the plasma nucleus
- Even when the arc plasma discharges were under extremely lean conditions at λ = 1.6, stable combustion occurred until the flames reached the chamber walls
- A comprehensive analysis of flames and combustion pressure showed that replacing point sparks with arc plasma discharges in engines will improve the fuel efficiency and output and also reduce the emission of harmful gases

## ACKNOWLEDGEMENT

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