

# Analysis of Plasma Flame Shapes using Combustion Visualized Chamber in a Gasoline Direct Injection Engine

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## Abstract

**Objectives:** This study attempted research to suggest the excellent result that increases the flame shapes, responses, energy of initial sparks and fuel efficiencies of plasma jet then the performance results using the conventional point spark at mixed condition ( $\lambda$  1.6) of a very rarefied air and gas including point of combustion limitation through the flame visualized chamber. **Methods/Statistical Analysis:** The experimental device was manufactured with the volume of the visualized chamber at 400cc to enable the observation of the flames of the conventional point spark and plasma jet. Moreover, the experiment was conducted under conditions including the most ideal excess air ratio ( $\lambda$ ) of 1.0 and the lambda ( $\lambda$ ), which is the extremely rarified mixture ratio, of 1.6 within the combustion chamber of the engine. **Findings:** As the result of the analysis of the expanding flame area, there was a further increase in the flame of the plasma jet over a very short period of time from 45ms to 50ms, with the display of the characteristic of expanding 30ms faster than the conventional point spark. **Application/Improvements:** From the experimental results, it was possible to arrive at the conclusion of the research that the combustion flame of the plasma jet has an improved combustion rate, flame characteristics and combustion characteristics in comparison to those of the conventional point spark since the plasma jet delivers powerful energy into the internal aspect of the visualized chamber even if it is mixed at a lean condition.

**Keywords:** Excess Air Ratio, Fuel Efficiency, Flame Shape, Lean-Burn, Plasma Jet

## 1. Introduction

New technology for combustion is being developed in order for the exhaust gases from the gasoline engine to satisfy the regulations of the US California Tier 3 (Motor vehicle emission and standard)<sup>1,2</sup>. Meanwhile, technology for catalyst for the filtering of the exhaust gases of gasoline engine are continuously being developed through extensive efforts in order to develop new material that can be used for such catalyst<sup>3</sup>. Moreover, technology for a reduction of the weight of the catalytic device is being gradually expanded<sup>4,5</sup>. In addition, a wide range

of technologies on new combustion are receiving the spotlight with the increase in the range of ideas that can be implemented concurrently with the catalytic technology of the exhaust gas through the technology development on new combustion<sup>6,7</sup>. The core aspect of the gasoline engine is known to be the combustion technology to which 3 factors are applied. In the event of improving the fuel efficiency of the combustion, it is possible to satisfy the reduction effect of the exhaust gas by reducing the proportion of the fuel use simultaneously<sup>8</sup>. In particular, it is possible to anticipate an affirmative effect for the ignition format using plasma, when applied to the engines,

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through the convergence of application technologies. Preceding research on plasma are divided largely into Arc, Corona, Microwave and Laser, and only preliminary research with the level of technology for the presentation of the differentiated performance outcomes through the realization of the energy of plasma were examined<sup>9</sup>. Therefore, this study attempted research to suggest the excellent result that increases the flame shapes, responses, energy of initial sparks and fuel efficiencies of plasma jet then the performance results using the conventional point spark at mixed condition ( $\lambda$  1.6) of a very rarefied air and gas including point of combustion limitation through the flame visualized chamber.

## 2. Experimental Devices and Methods

An experimental schematic using this research shows at Figure 1, and Table 1 and 2 shows in detail specifications. A flame visualizing chamber was designed by 400cc in order to visualize the flames with the conventional point sparks and plasma jets. Air fuel ratio of combustion was detected by an oxygen sensor which connected at analog communication port the signal of  $\lambda$  changes using control logic in software. The control logic of plasma jet designed the circuit to be possible to deliver at plugs over 45kV. Air fuel ratio accurately controlled of Air,  $C_3H_8$  and  $N_2$  after communicating the output signal and DAQ of MFC (mass flow controller). Created exhaust gas in a chamber after combustion was discharged into the atmosphere, and the pressure of combustion was designed for detecting the maximum pressure of flames after installation to an exhaust line.

Experimental method measured the compressed pressure that was set 6bar within a visualizing chamber after mixing Air fuel rate through the autonomously designed software, and experiment of reenact and repeatability for monitoring of combustion results was attempted. Also, the flames of the conventional point sparks and plasma jets was monitored with result that uses a high speed camera which is possible to detect 1,000fps. Experimental conditions show in detail with contents.

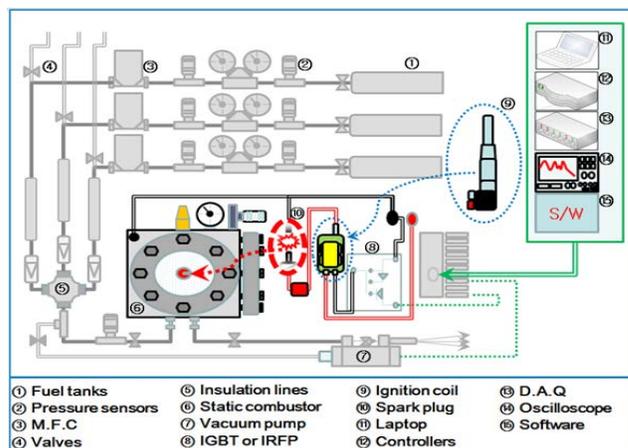


Figure 1. Schematic of a flame visualizing device

Table 1. Specifications a flame visualizing device

Items	Specifications
Pressure Sensors	- 0 to 250bar
M.F.C	- 0 to 10l/min
Check Valves	- 150bar
Chamber Volume	- 400cc
Oscilloscope	- 70MHz
Ignition Coil	- 15 to 25kV - Pencil
Spark Plugs	- Iridium - Plasma jet
HV Probe	- 500:1 - 1,000:1
Controller	- 1,000ms
Charging Valve	- 225bar
Vacuum Pump	- 18l/min

Table 2. Experimental conditions of the flame visualization

Properties	Conditions
Lambda[ $\lambda$ ]	- 1.0 (lean burn state within a chamber) - 1.6 (ideal state within a chamber)
Compressed pressure	- Fixed 6 bar
Gases	- Air, $C_3H_8$ and $N_2$
$N_2$ rate	- 0%, 10% (Assumed EGR)
Ignition types	- Point spark (Assumed Base) - Plasma jet (Experimental sample)
Ignition plugs	- Point type (iridium + platinum) - Plasma type (Platinum + nickel)
Assumed engine speed	- At 800rpm (engine idling state)
Chamber temperature	- At 80°C (standard GDI engine)
Ignition times	- At 1ms (point and plasma types)

### 3. Experimental Results and Discussions

Figure 2 shows the experimental results that visualized flames without nitrogen gas at  $\lambda$  1.0 after applying conventional point sparks and plasma jets with 6bar of compressed pressure. The flame result was analyzed at time between 0ms to 18ms to start the perfect combustion. Figure 2, (A) shows the results that analyze the flames characteristics of a conventional point spark. The analysis result of initial spark can verify a spark of point shape which was minutely created at 3ms point, and from 0ms to 2ms, it can verify a characteristic with having a delayed spark area. For this reason, because the amplified principle of 2 stages within an ignition coil was used, the generating result of spark at delayed time about 2ms could be noticeable.

The analysis result of expanding pressure layer could verify a characteristic to expand the pressure during 13ms with shape of ellipse from 4ms to 17ms. Also, the pressure layer could verify a result at 10ms of arrived time up to center. For this reason, Air fuel ratio became spent the time of average 13ms according to velocity of expanding pressure layer, and a characteristic was noticeable to have a shape of initial spark which affected by mixed ratio of air and gas.

The analysis result of completed pressure point could verify an arrived phenomenon a shape of pressure layer with flame on the wall of a visualizing chamber at 18ms, could examine the flame time to start at 19ms. For this reason, it is noticeable that expanding pressure layer was created by initial flame to arrive at maximum temperature point within a chamber.

The analysis result of expanding flame point could examine an extending flame at 20ms. For this reason, it may obtain a result to need 20ms with optimized response time if applying the most ideal condition as  $\lambda$  1.0 without  $N_2$  gas with compressed pressure 6bar.

Figure 2, (B) shows the result that analyzed the flame characteristics of plasma jet, and the result was analyzed with setting the equal scale as conventional point spark.

The analysis result of initial jet could examine a formed jet by plasma energy at 2ms point, and could verify the delayed spark area from 0ms to 1ms. For this reason, because energy that can discharge within circuit was additionally added, it was quickly discharged about 1ms then conventional point spark, and could be noticeable to reduce 1ms.

The analysis result of expanding pressure layer could examine a characteristic to expand the pressure during 7ms with wave shapes from 3ms to 10ms, and arrived time up to center of pressure layer could verify a differentiated characteristic at 7ms point. For this reason, because the temperature of plasma jet was maximized, the arrived time at center of pressure layer is noticeable to have a quickly responding characteristic about 3ms then conventional point spark.

The analysis result of completed pressure point could verify an arrived result on wall within a visualizing chamber at 10ms, and could examine starting flame point at 17ms. For this reason, because the inherent temperature having plasma jet is height, the completed pressure point is noticeable to be quick about 8ms then conventional point spark.

The analysis result of expanding flame point could examine a flame extending at 18ms. For this reason, if the most ideal condition at  $\lambda$  1.0 without nitrogen gas with compressed pressure 6bar applies, it may obtain an improving result that has a quick response about 2ms in case of plasma jet then conventional point spark.

Figure 3 shows the experimental result that visualizes the flames without nitrogen gas at  $\lambda$  1.6 of extremely rarefied state after applying the conventional point sparks and plasma jets with compressed pressure 6bar. Figure 3, (A) shows the analyzed result of a conventional point spark, and because air and fuel ratio was mixed as rarefied state, the flame results were analyzed from 25ms to 135ms.

The analysis result of delayed flame area could not indicate a phenomenon that generates the flames from 0ms to 50ms, and could verify the generating flame area at increasing temperature from 55ms to 65ms. For this reason, because air and fuel ratio was mixed by very rarefied condition, it is noticeable a reason that flame area was delayed.

The analysis result of expanding flame area has more increased the temperature within a visualizing chamber from 70ms to 80ms, and could verify the combustion area that maintains a stable state after generating flame from 85ms to 120ms. For this reason, although air and fuel ratio was mixed by a very rarefied condition, it is noticeable a reason that is sharply increased the temperature.

The analysis result of disappearing combustion area could show the final step of combustion that is gradually reduced from 125ms to 135ms, and could verify a characteristic that is maintained the increasing

temperatures and residual flames within a visualizing chamber. For this reason, after the combustion within a visualizing chamber was completed, because the flame within a chamber was not discharged from the inside outwards, a reason was noticeable that residual flame was remained.

Figure 3, (B) shows a result that analyzes the flame characteristics of plasma jet, and analyzed the results setting an equal scale as the conventional point spark.

The analysis result of delayed flame area was not indicated that the flame was generated from 0ms to 30ms, and could verify the delayed time that was reduced about 20ms then the conventional point spark. Also, the generating flame area was increased with temperature from 35ms to 40ms but, it could verify a quickly started characteristic about 25ms then the conventional point spark. For this reason, because the energy component of plasma jet has strong, a reason was noticeable that generating flame area was quickly started.

The analysis result of expending flame area has more increased during a short time from 45ms to 50ms, and indicated a quickly expending phenomenon about 30ms then the conventional point spark. Also, combustion area has maintained the equal state after generating the flame from 55ms to 100ms but, it could verify a combustion characteristic that was quickly started about 25ms then the conventional point spark. For this reason, the conventional point spark has a resistance layer that was not perfectly arrived at combustion wall in case of flame but, it was noticeable a result that the plasma jet has the energy that can perfectly arrive at combustion wall.

The analysis result of disappearing combustion area could verify a quickly disappearing characteristic about 20ms then the conventional point spark. For this reason, it was noticeable a reason that plasma jet had an ignition advanced time of combustion because the flame was quickly started then conventional point spark.

Figure 4 show the results that apply nitrogen gas with 10% at lambda 1.0 after of the conventional point sparks and plasma jets with compressed pressure 6bar. Also, if the experiment does experimental work at lambda 1.0 that was applied over 10% with nitrogen gas, the chemical quenching phenomena to be affected by worst influence in flame performance of rarefaction critical point may generate. Therefore, this result was suggested just with experimental result up to nitrogen gas 10% at lambda 1.0.

Figure 4, (A) shows the analysis result of the

conventional point spark, and it was analyzed the flame result from 10ms to 120ms of delayed time after charging 10% nitrogen gas.

The analysis result of delayed flame area was not indicated about generating phenomenon of flame from 0ms to 35ms. Also, it could verify a delayed result about 33ms then lambda 1.0 without nitrogen gas. The analysis result of generating flame area could verify a result that sharply increases the temperature to affect the residual spark within a chamber between 40ms and 50ms, and could verify a delayed characteristic about 30ms then lambda 1.0 without nitrogen gas. For this reason, because nitrogen gas was assumed as EGR ratio, it could analyze a result to have a resistance in area where is possible to make flame then lambda 1.0 without nitrogen gas.

The analysis result of expending flame area shows a expending phenomenon with flame between 55ms to 65ms, and could verify the combustion area that maintains the stable combustion state between 70ms to 95ms. For this reason, although nitrogen gas of 10% adds, it could obtain a result that maintains the stable combustion state because the condition according to basic mixing ratio of air and gas.

The analysis result of disappearing combustion area could examine a slowly reduced characteristic surrounding 100ms, and could verify a characteristic that maintains the increased temperature and residual flame within a visualizing chamber with similar result as lambda 1.6 without nitrogen gas. For this reason, after the combustion within a visualizing chamber was completed, because the flame within a chamber was not discharged from the inside outwards, a reason was noticeable that residual flame was remained.

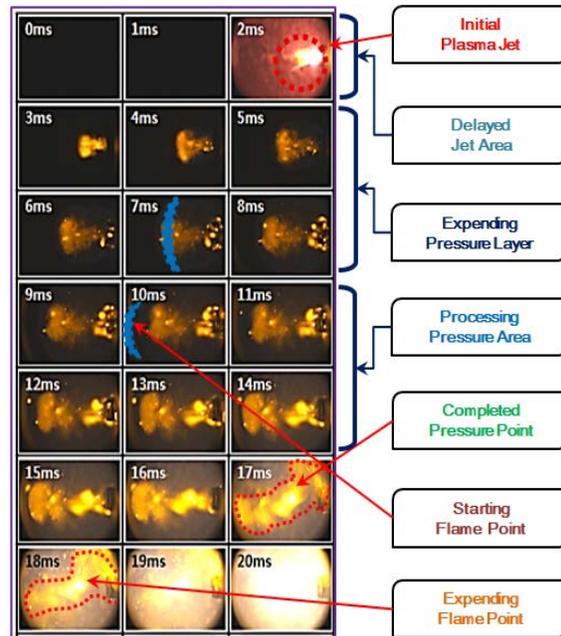
Figure 4, (B) shows the result that analyzes the flame characteristics of plasma jet at applying lambda 1.0 after charging nitrogen gas 10%, and the plasma jet can show a characteristic that was not exist at delayed flame area.

The analysis result of expending pressure layer could verify the flame waves according to plasma jet up to 20ms, and could verify a characteristic that sharply increases the temperature by strong residual plasma then the conventional point spark between 25ms and 35ms. Also, the time of expending flame area could verify a characteristic of velocity that was quickly delivered about 25ms then the conventional point spark. For this reason, although nitrogen gas of 10% adds at lambda 1.0, it was noticeable a reason that was quickly started by flame area

because the plasma jet has a very strong energy then the conventional point spark.

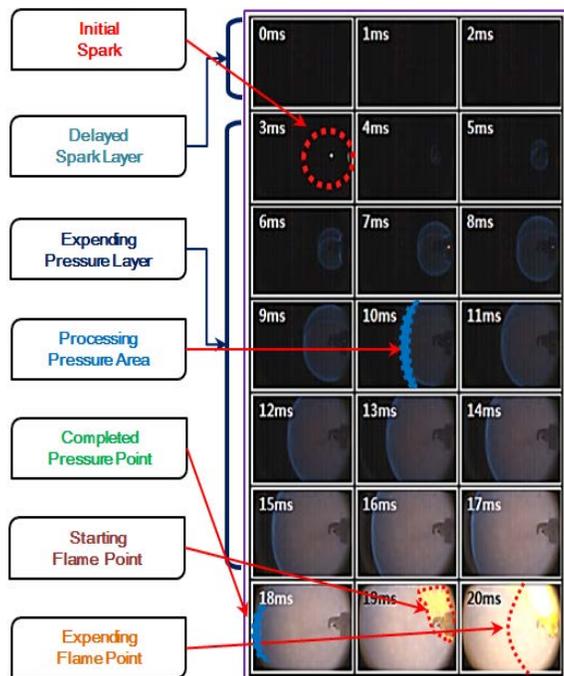
The analysis result of expanding flame area has more increased the flame during a short time from 45ms to 50ms, and indicated a phenomenon that was quickly expanded about 30ms then the conventional point spark. Also, the combustion areas had maintained the stable state after generating the flame from 55ms to 100ms but, it could verify a quickly started combustion characteristic about 25ms then the conventional point spark. For this reason, the conventional point spark has a resistance layer that was not perfectly arrived at combustion wall in case of flame but, it was noticeable a result that the plasma jet has the energy that can perfectly arrive at combustion wall.

The analysis result of disappearing combustion area could examine a slowly disappeared characteristic up to 95ms, and could verify a quickly disappearing characteristic about 20ms then the conventional point spark. For this reason, it was noticeable a reason that plasma jet had an ignition advanced time of combustion because the flame was quickly started then conventional point spark.

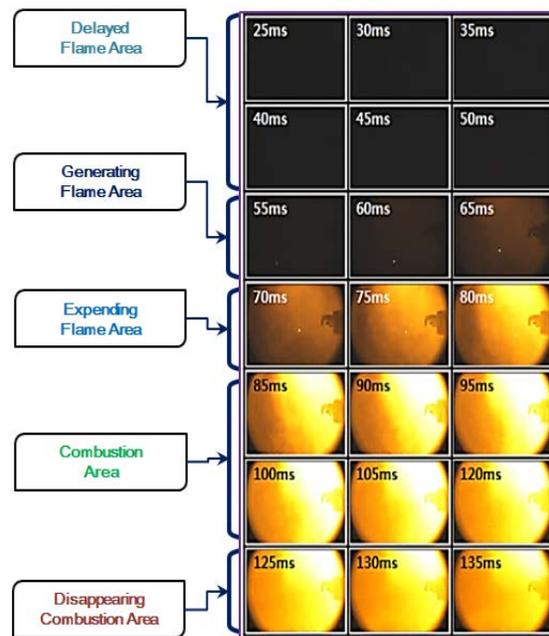


(B). Plasma jet type

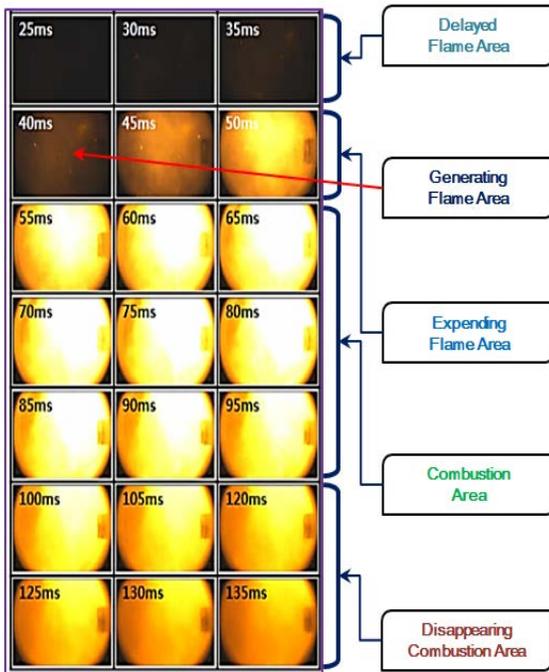
Figure 2. Visualized results of lambda 1.0 without nitrogen gas.



(A). Conventional point spark type

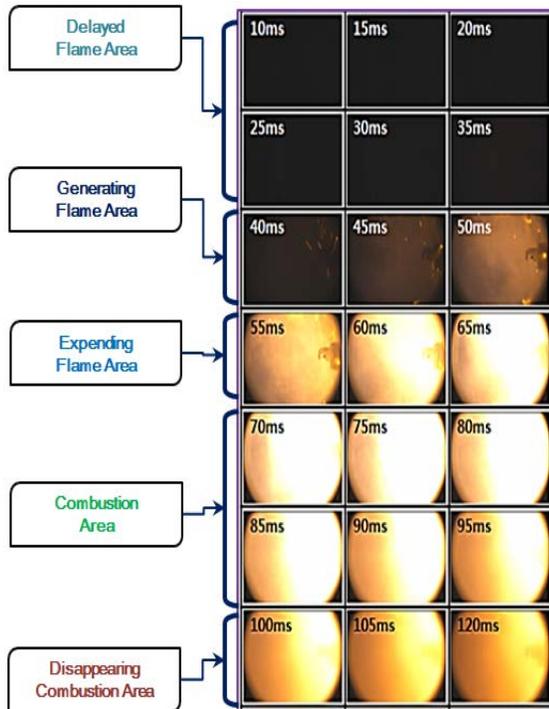


(A). Conventional point spark type

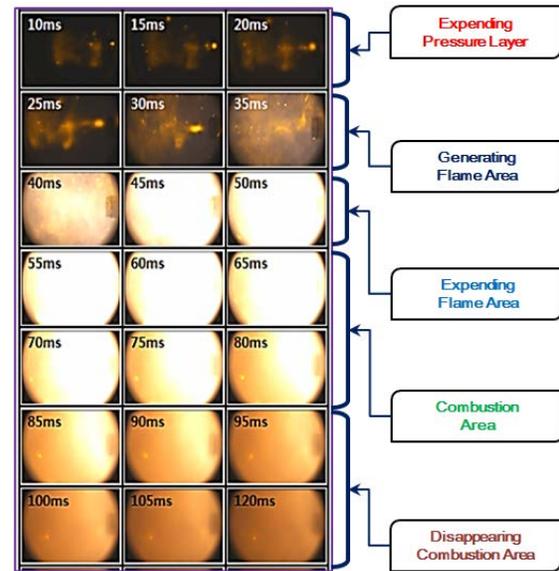


(B). Plasma jet type

Figure 3. Visualized results of lambda 1.6 without nitrogen gas.



(A). Conventional point spark type



(B). Plasma jet type

Figure 4. Visualized results of lambda 1.0 after applying nitrogen gas 10%.

## 4. Conclusions

The analyzing result of flame shapes after applying the conventional point sparks and plasma jets using a flame visualizing chamber can be obtain the conclusion as follows:

- In case of lambda 1.0 without nitrogen gas, the plasma jet has a characteristic that quickly generates about 1ms then response time of the conventional point spark, and it was noticeable to have a quick response about 8ms then the conventional point spark at arrived time on a visualizing chamber of pressure layer.
- In case of lambda 1.6 without nitrogen gas, the plasma jet has a quick characteristic about 30ms of time that generates the flame then the conventional point spark, and although air and gas ratio was mixed as rarefied condition, it was noticeable to reduce a unburned characteristic within a visualizing chamber.
- In case of lambda 1.0 after charging nitrogen gas 10%, the conventional point spark has indicated a delayed characteristic by resistance component of nitrogen gas up to 35ms. However, it is noticeable the plasma jet was not exist of delayed time in spite of adding the nitrogen gas 10%.

- A spark size was greatly affected by combustion according to generating volume within a visualizing chamber, and if the maximized energy as plasma jet applies in engines, it may expect the outstanding performance in terms of power and fuel efficiency.
- The plasma jet is surely necessary a method to delay of ignition time because of quickly generating then the conventional point spark, and if engine experiment does work, it is consider contributing in the very outstanding research results then the conventional point spark.

## 6. Postscript

This study was attempted to analyze the experimental flames with nitrogen gas 10% of the most ideal lambda 1.0 and the most rarefied 1.6 within the combustion area using the conventional point sparks and plasma jets. In additional experiments, nitrogen gas set the condition from 0% to 20% with 5% units using the plasma jet, and lambda will be slated to suggest the research results through setting from 1.0 to 1.6 with 0.2 units.

## 6. Acknowledgement

“This work was supported by the Research Grant of the Kongju National University in 2015”

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