

The Influence of Hot Gas Jet on Combustion Enhancement for Lean Mixture in Plasma Jet Ignition

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ABSTRACT

This study clarified the influence of hot gas jet on combustion enhancement effect for lean mixture in the plasma jet ignition. The hot gas jet was generated by the high temperature plasma and was ejected from igniter after plasma jet finished issuing. In combustion tests, propane-air mixture at equivalence ratio of 0.6 was used and the mixture was filled in the combustion chamber at atmosphere pressure and room temperature. For generation of the hot gas jet, the standard air was filled in chamber at same conditions and the hot gas jet was visualized by schlieren method in the absence of combustion. The combustion development processes were also visualized and the combustion pressure was measured. The discharge voltage, discharge current and the plasma luminescence were also measured. The plasma luminescence disappeared within 0.05 ms for any experimental conditions. When cavity depth was deep and orifice diameter was small, the maximum plasma luminescence height was short. However, the hot gas jet ejection velocity was increased as the cavity volume increased and orifice diameter decreased. At 0.5 ms after the ignition, both initial flame kernel and hot gas jet were similarly developed. However, the combustion was continuously enhanced after the hot gas jet disappeared. This is because the initial flame kernel was enlarged and turbulence was generated on flame front by the hot gas jet effect. In case of a large volume cavity and small diameter orifice of igniter, the flame propagation was enhanced and combustion duration was shortened. The high voltage discharge duration was very short as compared with combustion period and the initial flame kernel was similarly developed as hot gas jet, therefore the combustion enhancement effect of plasma jet ignition was mainly caused by the hot gas jet effect.

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INTRODUCTION

Recently, the climate change caused by the global warming is most important environmental problem to have to solve. The global warming is mainly generated by the carbon dioxide emitted to atmosphere, therefore the carbon dioxide emission should be urgently reduced. The carbon dioxide emitted from transportation sector accounts for about 20 % of total emission.⁽¹⁾ Therefore, the carbon dioxide emitted from spark ignition and compression ignition engines equipped on vehicles must be decreased to protect the global environment. For a spark ignition engine, many investigations have been studied to improve the fuel consumption without deteriorating exhaust gas emission characteristics, for examples, the high compression ratio⁽²⁾ and the downsizing engine⁽³⁾. The lean combustion has been also noticed because the specific fuel consumption could be improved due to an increase of ratio of specific heat, and a decrease of heat loss

and pumping loss. However, in the lean combustion, the ignitability is deteriorated and the flame propagation velocity is very low as compared with those of stoichiometric mixture. Many kinds of combustion and ignition method were studied to realize the lean combustion such as the multi point ignition⁽⁴⁾, the high energy ignition⁽⁵⁾ and the swirl and tumble flow in combustion chamber⁽⁶⁾. The plasma jet ignition has been investigated as one of the most effective methods to solve these disadvantages simultaneously^{(7),(8),(9),(10)}. Figure 1 shows the plasma jet igniter configuration. The plasma jet igniter consists of three parts: cavity that is a cylindrically shaped hole, a circular orifice and a central electrode. The cavity is a hole which is drilled in Teflon pole and the central electrode is isolated from combustion chamber body by Teflon pole. In the procedure of plasma jet ignition, the high-voltage electrical discharge occurs between the tip of central electrode and orifice plate, and the electrical energy is given to the gas in a cavity. Then, the gas in the

cavity changes the plasma state and the plasma jet is ejected into the combustion chamber by the high-pressure in the cavity.⁽¹⁰⁾ The lean mixture is surely ignited by the high energy plasma and the combustion is enhanced by the fluid effect of plasma jet, so that the plasma jet ignition has features of both high energy ignition and pre-chamber combustion. In plasma jet ignition, radicals generated by the high temperature plasma also improve both ignition and combustion phenomena. Therefore, it was found in previous studies that there were three combustion enhancement effects in plasma jet ignition: these were the high energy effect, jet effect and activated radical effect.

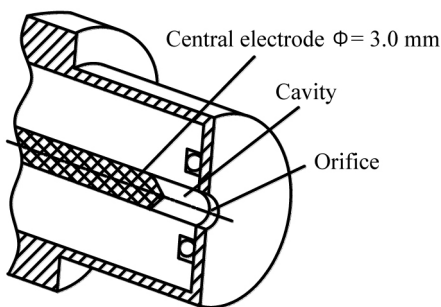


Figure 1. Igniter configuration.

In this study, a new combustion enhancement factor has been proposed for plasma jet ignition and it was the hot gas jet effect. The hot gas jet was the high temperature gas jet and it was generated by the high temperature plasma. The hot gas jet was ejected from igniter after plasma jet finished issuing. This study clarified the influence of hot gas jet on combustion enhancement effect for lean mixture by using a constant volume combustion vessel. The combustion characteristics were explored by visualizing the flame propagation processes and measuring the combustion pressure records. The plasma luminescence was observed to clarify the process of growth of plasma jet and both discharging voltage and current were also measured. The cavity depth and orifice diameter, and the discharging voltage were varied to clarify the influence of the igniter configuration and discharging energy on the plasma jet and hot gas jet development processes and the process of growth of plasma jet.

EXPERIMENTAL APPARATUS AND TEST PROCEDURE

Figure 2 shows the schematic diagram of experimental apparatus. The experimental apparatus consists of plasma jet igniter, combustion chamber, capacitance high-voltage discharge circuit, pressure measurement system, schlieren system with a digital high-speed camera and the image analyzing system. The combustion chamber had a cylindrical shape with 80 mm of diameter and 40 mm of thickness, so that the combustion chamber volume was 201 cm³. The igniter was attached to the bottom of combustion chamber and two quartz observation windows were fixed on both sides

of combustion chamber for the visualization of schlieren system. The pressure sensor was set in the side of the combustion chamber horizontally.

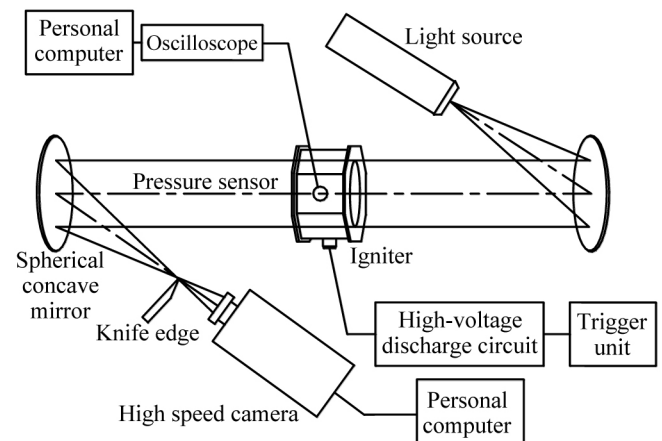
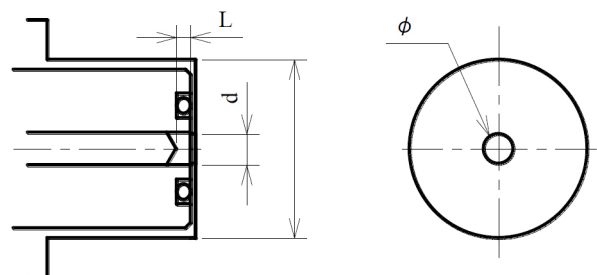


Figure 2. Schematic diagram of the experimental apparatus.

Figure 3 shows the detail of plasma jet igniter. The cavity diameter was always 3.0 mm and the cavity volume was varied by changing the cavity depth. Here, the cavity depth was defined as length between the tip of central electrode and the inner wall of orifice plate and was varied as 3.0, 4.0, 5.0, 6.0 and 7.0 mm. The orifice diameter was also varied as 1.0, 2.0 and 3.0 mm. The diameter of central electrode was the same as that of cavity: 3.0 mm, and the tip of central electrode was pointed as 120 deg. The central electrode was made by tungsten in order to avoid wearing by the high-voltage electrical discharge. In case of the conventional combustion, the mixture was ignited by a spark plug whose gap was 1.5 mm and the ignition energy was about 2.5 J.



Cavity diameter $d=3.0$ mm
Cavity depth $L=3.0, 4.0, 5.0, 6.0, 7.0$ mm
Orifice diameter $\phi=1.0, 2.0, 3.0$ mm

Figure 3. Details of plasma jet igniter.

The capacitance high-voltage discharge circuit was started by the three-point gap switch which had two ball electrodes and the trigger system shown in figure 4. The three levels of electrical energy was charged in capacitor of which capacitance was 0.1 μ F and electrical supplied energies of 2.5, 5.0 and 10 J was stored at 7.1, 10 and 14 kV of charging

voltage, respectively. To prevent the break down through the gap of two ball electrodes, the gap lengths were selected as 4 mm for electrical supplied energy of 2.5 J and 6 mm for 10 J, respectively. For electrical supplied energy of 5.0 J, both gap lengths, 4 and 6 mm, were tested and, the electrical supplied energy of 5.0 J with gap lengths 4 and 6 mm were expressed by “5 J-4” and “5 J-6” in figures and tables, respectively.

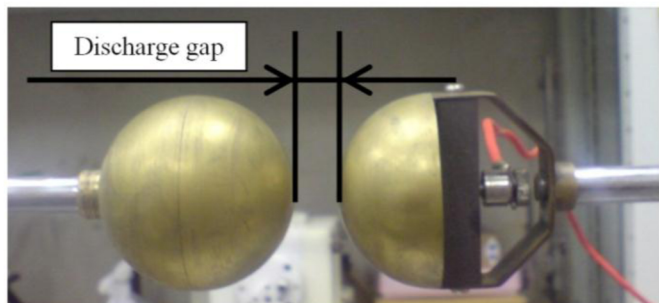


Figure 4. The three-point gap switch to start the electrical discharge.

In cases of measurement of plasma luminescence, the plasma jet was directly taken by a digital high-speed camera (450000 frame/s and shuttering speed of 1/450000 s), and the discharging voltage and current were simultaneously measured. The discharging voltage was detected between central electrode and combustion chamber body which was earthed. The discharging current was measured by the wire cramp type current probe. Signals of discharging voltage and current were synchronized with images of plasma jet by using an A/D conversion board with digital high-speed camera, therefore the process of growth of plasma jet could be compared with the high-voltage electrical discharge process. When the process of growth of plasma jet was observed, the standard air was filled in chamber at atmosphere pressure and room temperature.

In combustion tests, propane-air mixture at equivalence ratio of 0.6 was used and the mixture was filled in the combustion chamber at atmosphere pressure and room temperature. For generation of the hot gas jet, the standard air was filled in chamber at the same conditions, so that the hot gas jet development process was observed in the absence of combustion. The hot gas jet growth and combustion processes were visualized by the conventional type Z shape schlieren system and were taken by a digital high-speed camera (20000 frame/s and shuttering speed of 1/30000 s). The schlieren images were memorized in the personal computer and were analyzed by using the image analyzing system. The binary image analyzing method was applied and the distance between top of flame front or hot gas jet and plasma jet igniter was measured along the central axis of combustion chamber at arbitrary time from the electrical discharge to analyze both combustion and hot gas jet development processes. The image analyzing was continued until the flame front or hot gas jet reached to the combustion

chamber wall located at the opposite side of plasma jet igniter.

RESULTS AND DISCUSSION

Plasma Jet Luminescence and Electrical Discharge Characteristics

Figure 5 shows electrical discharge waveforms and plasma luminescence as a function of time from the electrical discharge. The upper figure shows discharging voltage and current, and plasma luminescence height ratio, and the lower figure shows discharging voltage and current, and plasma luminescence area ratio. Here, the plasma luminescence height ratio was non-dimensional plasma jet height and the plasma jet luminescence height at an arbitrary time was divided by the diameter of combustion chamber. The plasma luminescence area ratio was non-dimensional plasma jet area and the plasma jet luminescence area at an arbitrary time was divided by the cross sectional area of combustion chamber. The plasma jet igniter configuration of 5.0 mm of cavity depth and 1.0 mm of orifice diameter was used for all cases.

When the electrical supplied energy was small or the gap length was long for the same electrical supplied energy, the start of electrical discharge was delayed, because the discharge resistance of gap interfered with the electrical discharge. In any cases, the damped oscillation waveform was shown for both electrical discharging voltage and current. The plasma luminescence began to observe immediately after the electrical discharging start and the plasma luminescence continued emitting after the electrical discharge was finished. Therefore, the plasma jet starts to issue from the igniter at the same time of electrical discharge occurrence and the plasma which is contained and remained in cavity continues issuing after the electrical discharge is completed. In all cases, the plasma luminescence disappeared within 0.05 ms after the electrical discharge start, so that the plasma jet could be existing very short duration as compared with the combustion period.

The plasma luminescence height ratio increased as a time elapsed, although the discharging electrical voltage and current were decreased. It can be considered that the high pressure in cavity created by electrical discharge makes the plasma jet keep issuing, so that the increasing tendency of growth of plasma luminescence height ratio is slowed down as the time elapses. In the lower figure, the plasma luminescence area ratio also increased as a time elapsed, however the plasma luminescence area ratio decreased after it showed the peak. This is because a plasma jet gradually disappears from its surround while the plasma jet still proceeds to progress as show in table 1. In the case of same the electrical supplied energy 5.0 J, the plasma luminescence height ratio and area ratio indicated the almost the same tendency for both gap length, so that, the growth of plasma jet was not influenced by the gap length. The maximum plasma luminescence area ratio increased as the electrical