Combustion Enhancement by Plasma Jet Ignition in Lean Mixtures

Shinsuke ONO**, Eiichi MURASE**, Kunihiko HANADA** and Keiichi FUJIKI**

In order to confirm the performance and characteristics of plasma jet ignition quantitatively, combustion tests were carried out by varying the governing parameters of the plasma jet ignition. Three plasma cavities of 37, 75, and 170 mm³, two orifices with diameters of 1 and 2.5 mm, and three discharge energies of 0.3, 1.5, and 6.7 J were tested in two different types of combustion vessels with lean hydrogen–air mixtures at equivalence ratios of 0.3 and 0.4. From a series of tests, the combustion enhancement by the plasma jet ignition is revealed only in the initial stage of combustion. Then a comparing parameter for the performance of plasma jet ignition in its initial stage of combustion is proposed by comparing the pressure diagram of plasma jet ignition with that of conventional single-point center ignition. The performance and the characteristics of plasma jet ignition are revealed quantitatively by the comparing parameter.

**Key Words**: Combustion, Internal Combustion Engine, Combustion Enhancement, Plasma Jet, Ignition, Lean Mixture, Hydrogen

1. Introduction

In order to improve the exhaust emission characteristics and the thermal efficiency of internal combustion engines, a great deal of interest has been generated regarding the combustion of lean mixtures. However, lean mixtures are more difficult to ignite reliably and have a lower burning rate in contrast with a stoichiometric mixture. Accordingly, enhanced ignition is of particular importance to lean-burn internal combustion engines. Plasma jet ignition (PJI) is one of the prospective enhanced ignition systems, and it has a great potential to improve the ignition reliability and the burning rate of lean mixtures.

Among the many studies of PJI(1)–(5), there are very few reports about the comparing parameter or the index of the performance of PJI. Only Mittinti and Dabora(5) introduced the combustion index to evaluate the effectiveness of PJI from the combustion pressure record, which represented the overall effects of PJI including the heat losses to the combustion chamber walls. Therefore, the purpose of this paper is to establish a comparing parameter for the performance of PJI, especially its initial stage of combustion where the pure performance of the jet can be seen, and to confirm the performance and characteristics of PJI quantitatively.

2. Experimental Apparatus and Procedure

The plasma jet (PJ) igniter used in the experiment is shown in Fig. 1, and its ignition circuit is shown in Fig. 2. The insulator and the side wall of the plasma cavity are made out of teflon, and the center electrode (cathode) and the orifice plate (anode) are made out of tungsten rod and stainless steel, respectively. The plasma cavity is cylindrical in shape with a length of 6 mm. Three inside diameters (2.8, 4, 6 mm) were used to vary the cavity volume by changing the teflon inserts, and these provided the plasma cavity volumes of 37, 75, and 170 mm³, respectively. The orifice plate is also changeable to allow for a
change in the discharge orifice size. Two orifice sizes were provided, namely 1 mm and 2.5 mm in diameter, while the thickness of both plates was constant at 1 mm.

The ignition circuit consists of two parts. One is the trigger circuit which consists of a conventional electronic ignition system for automotive use. The other is an add-on system which supplies the main energy to the PJ igniter by discharging the energy stored on the capacitor, C, at a relatively low voltage (~4 kV). This system operates in the following manner. When the ignition module is triggered by an electric pulse, the induced high voltage by the coil initiates breakdown in the PJ igniter. Once the igniter breaks down, the add-on circuit is closed and the energy storage capacitor, C, discharges through the PJ igniter. In the experiments, the value of the capacitor, C, was held constant at 1.0 μF, and the stored energies were varied by changing the charged voltage. Energies of 0.3, 1.5, and 6.7 J were tested.

Combustion tests were conducted using two types of combustion vessels. One is the combustion vessel I shown in Fig.3(a). The shape is approximately cylindrical (200 mm in diameter by 200 mm in length), and its volume is 5110 cm³. The vessel is fitted with two optical glass windows 80 mm in diameter which face each other, and two stirring fans are installed, as shown in Fig.3(a). The gaseous fuel and the air are introduced separately into the vessel based on the partial pressures of components, and then mixed by the fans to make a homogeneous mixture.

The other is the combustion vessel II (Fig.3(b)) which is smaller in volume than the combustion vessel I. The shape of the vessel is a rectangular prism 50 mm long, 50 mm wide and 125 mm high, and its volume is 360 cm³. The two optical glass windows are 45 mm x 100 mm and face each other. The gaseous fuel and the air are introduced into the vessel in the same manner as in the vessel I, however, the fuel and the air are mixed by a circulating fan which is installed outside of the vessel.

Combustion tests using a conventional ignition system with two pointed electrodes were also made, the data of which acted as the reference for the comparisons. For this experiment, the two pointed electrodes were positioned so that the ignition process was initiated at the center of each combustion vessel. The spark gap was set to 3 mm.
For the combustion tests reported in this paper, lean hydrogen-air mixtures at equivalence ratios of 0.3 and 0.4 were used, and the combustion tests were carried out with the mixtures initially quiescent and at atmospheric pressure and room temperature. The plasma cavity was filled with the same mixture as in the combustion chamber. The combustion tests were carried out ten times for each test condition (Table 1). Photographic records of the combustion events were also obtained by schlieren photography.

3. Experimental Results and Discussions

3.1 Combustion pressures and the schlieren photographs

Figures 4～6 show typical examples of the combustion pressures in the vessel I at an equivalence ratio of 0.4 (pressure curves are the average of ten measurements). In the figures, $P^*$ denotes the gauge pressure, "Normal" denotes single-point center ignition by the conventional ignition system, and the discharge energy, $E$, is chosen equal to the stored energy on the capacitor.

From Figs.4～6, PJI shows a more rapid pressure rise than "Normal" ignition. However, the peak pressures reached by PJI are slightly lower than that by "Normal" ignition. This is thought to be caused by a larger heat losses to the combustion chamber walls by PJI than "Normal" ignition. In the case of "Normal" ignition, the heat losses to the chamber walls appears only in the final stage of combustion, however, for PJI, the turbulent plume impinges on the chamber walls. It is this difference in the form of flame propagation that presumably causes the differences in the peak pressures.

Figures 7(a)～(f) show typical examples of schlieren photographs of the combustion phenomena by "Normal" ignition and PJI at an equivalence ratio of 0.4. From Figs.7(b)～(f), the appearances of the flame propagation in PJI are quite different from "Normal" ignition (Fig.7(a)), and the initial flame area of PJI is much larger than that of "Normal" ignition.

The influences of the discharge energy are seen in Fig.4 and Figs.7(b) and (c). The discharge energy determines the initial state of the gas in the cavity, and affects both the chemical and the aerodynamic aspect of the plasma jet. The pressure curve rises rapidly with an increase in the discharge energy from 0.3 J to 6.7 J (Fig.4), and the growth rate of the plume also increases with an increase in the discharge energy (Figs.7(b) and (c)).

The influences of the discharge orifice diameter are seen in Fig.5 and Figs.7(b) and (d). The cavity volume and the orifice diameter affect the aer-

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<th>Test Conditions</th>
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<tr>
<td>equivalence ratio</td>
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<td>stored energy (J)</td>
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<td>cavity volume (mm$^3$)</td>
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<td>orifice diameter (mm)</td>
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Fig. 5 Influence of the discharge orifice diameter, $d$ (equivalence ratio=0.4, Vessel I)

Fig. 4 Influence of the discharge energy, $E$ (equivalence ratio=0.4, Vessel I)

Fig. 6 Influence of the cavity volume, $V_p$ (equivalence ratio=0.4, vessel I)

Series II, Vol. 32, No. 4, 1989

JSME International Journal
odynamic aspect of the plasma jet. The pressure curve for the orifice diameter of 1 mm increases more rapidly than that for the diameter of 2.5 mm (Fig. 5), and the shape and the growth of the turbulent plume are quite different (Fig. 7(b) and (d)). The penetration depth and the growth rate of the plume increase with a decrease in the orifice diameter from 2.5 mm to 1 mm.

The influences of the plasma cavity volume are seen in Fig. 6 and Figs. 7(e) and (f). From Fig. 6, the pressure curve increases more rapidly with an increase in the plasma cavity volume from 37 mm$^3$ to 170 mm$^3$. From Figs. 7(e) and (f), the growth rate of the turbulent plume increases with an increase in the cavity volume. The amount of reactive material increases with an increase in the cavity volume, however, a too large cavity volume decreases the degree of the activated state of the gas in the cavity.

3.2 The comparing parameter for the performance of PJI

The most interesting feature obtained from Figs. 4–6 is that the pressure diagrams of PJI and "Normal" ignition, except for the initial and peak regions, approximately coincide with each other when shifted.

Fig. 7 Schlieren photographs of the combustion phenomena by "Normal" ignition and PJI
(equivalence ratio = 0.4, interframe time; (a) – (d) = 0.8 ms, (e), (f) = 1 ms)
with respect to time. This suggests that the combustion enhancement by PJII occurs only in the early stages of combustion, and does not continue throughout the combustion period.

The mechanism of combustion enhancement by PJII is thought to be as follows. When the high energy is discharged into the plasma cavity, a high-temperature plasma is created so rapidly that the cavity is pressurized and the plasma jet is issued through the orifice into the combustion chamber. The plasma jet penetrates into the combustion chamber with entraining the surrounding mixture, and forms the turbulent plume. In the turbulent plume, there are considerable amounts of radicals, so that after a very short induction time, the ignition takes place similar to the multipoint ignition. Consequently, the combustion proceeds at a high rate. However, the effect of the turbulent plume presumably dissipates very rapidly, and the flame may acquire a more laminar structure. Therefore, after a certain time period from the ignition, the combustion pressure rise becomes as same as that of "Normal" ignition where the flame propagates spherically by its laminar flame velocity.

From the above discussion, the combustion enhancement by PJII is present until the combustion pressure rise becomes as same as that of "Normal" ignition. Therefore, the amount of reduction time by PJII to attain the same combustion pressure rise as "Normal" ignition signifies the degree of combustion enhancement by PJII, and the reduction time can be derived using the following combustion model.

When a quiescent mixture is ignited by a single-point source at the center of a spherical combustion vessel, the following relation is obtained:

\[ P^* = \frac{C_i}{V_c} \tau^3 \]  
(1)

where \( P^* = P - P_0 \), \( P \) is the pressure at time \( \tau \), \( P_0 \) is the initial pressure, \( V_c \) is the combustion chamber volume, and \( C_i \) is the mixture-dependent constant. Equation (1) is valid in both the cylindrical and the rectangular combustion vessel at least before the flame reaches the combustion chamber wall, or the early stages of combustion. In the case of combustion by PJII, the plasma jet entrains the mixture and forms the turbulent plume where the ignition takes place and burns rapidly, as mentioned previously.

Let \( m_i \) be the mass of the mixture which is entrained in the plasma jet and burns rapidly during the period of \( \tau \). During this period, the turbulent plume grows mainly in the direction of the jet. Therefore, its growth can be taken as one-dimensional, and we assume that the pressure rise during \( \tau \) is proportional to the time. Thus,

\[ P^* = \frac{C_i}{V_c} \tau \quad (0 \leq \tau \leq \eta) \]  
(2)

where \( C_i \) is a constant which depends on the entrainment velocity and the burning rate of mass, \( m_i \). After \( \eta \), the combustion pressure rise by PJII is equal to that of "Normal" ignition. Therefore, the pressure diagrams of PJII and "Normal" ignition can be estimated from the above assumptions, as in Fig. 8. After \( \eta \), the pressure rise by PJII is given by shifting the pressure diagram of "Normal" ignition with respect to time.

Let \( \Delta \tau \) be the amount of this shift, and the combustion pressure for PJII after \( \eta \) is given by

\[ P^* = \left( \frac{C_i}{V_c} \right) (\tau + \Delta \tau)^3 \quad (\eta \leq \tau) \]  
(3)

Therefore, the time difference, \( \Delta \tau \), to attain the same combustion pressure for both PJII and "Normal" ignition before \( \eta \) is obtained by Eq.(4), and after \( \eta \), \( \Delta \tau \) is obtained by Eq.(5) as follows:

\[ \Delta \tau = \left( P^* V_c/C_i \right)^{1/3} - \left( P^* V_c/C_i \right) \quad (0 \leq P^* \leq P^*_\eta) \]  
(4)

\[ \Delta \tau = \Delta \tau_\eta = \left( P^* V_c/C_i \right)^{1/3} - \left( P^* V_c/C_i \right) \quad (P^*_\eta \leq P^*) \]  
(5)

where \( P^*_\eta \) is the combustion pressure by PJII at \( \eta \). The reduction time, \( \Delta \tau_\eta \), is the comparing parameter of the combustion enhancement by PJII. The function expressed by Eq.(4) takes a maximum value, \( \Delta \tau_{\text{max}} \), at the pressure of \( P^*_\eta \) which is given as follows:

\[ \frac{P^*_\eta}{P^*} = \frac{1}{\eta V_c \sqrt{27 C_i}} \]  
(6)

When \( P^*_\eta < P^* \), the maximum appears, and when \( P^*_\eta > P^* \), the maximum does not appear.

From Eqs.(2) and (6),

\[ \frac{P^*_\eta}{P^*} = \frac{1}{\eta V_c \sqrt{27 C_i}} \]  
(7)

Therefore, whether the maximum of \( \Delta \tau \) will appear or not depends on the values of \( C_i \), \( C_\eta \), and \( \eta \).

When the same mixture is used \( (C_i = \text{const}) \), the value of \( P^*_\eta/P^* \) depends on the values of \( C_\eta \) and \( \eta \). The value of \( C_i \) depends on the entrainment velocity and the burning rate of mass, \( m_i \), and the value of \( \eta \) depends on the amount of mass, \( m_i \). Thus, the value of

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**Fig. 8** Assumed pressure diagrams of PJII and "Normal" ignition
$P_0^* / P^*$ depends on the characteristics of the formation of the turbulent plume. In the case of $P_0^* < P^*$, $\Delta r$ decreases in the region of $P_0^* < P^* < P_0^*$, which means that in this region, the propagation rate of the spherical flame (three-dimensional) surpasses the propagation rate by PJII (one-dimensional). Figure 9 shows the relation between $\Delta r$ and $P^*$. In the figure, region I indicates Eq. (4), and region II indicates Eq. (5) (for the case of $P_0^* < P_0^*$).

In the later region of combustion, the heat losses to the combustion chamber walls by PJII is larger than that by "Normal" ignition, as mentioned previously, so $\Delta r$ will decrease. This region is shown as region III in Fig. 9.

In order to verify the above relation, the variations of $\Delta r$ with $P^*$ are plotted and typical examples are shown in Fig. 10. Figure 10 shows the validity of the above assumptions.

Lewis and von Elbe deduced that the fraction of the pressure rise is approximately proportional to the fraction of the mass burned, so the fraction of $m_1$, to the total mass of the mixture, $m_e$, can be expressed as follows:

$$P_i - P_o = P_i^* - P_o^* = m_e = m_1 / C_3 V_c$$

where $P_i$ is the maximum pressure, and $C_3$ is a constant which depends on the mixture.

Then,

$$P_i^* = P_i^* m_1 / (C_3 V_c)$$

Substitution of Eq. (9) in Eq. (5) then gives

$$\Delta r_p = \left( P_i^* m_1 / C_3 C_5 \right)^{1/3} - P_i^* m_1 / C_3 C_5$$

where $K_i$ is a constant which depends on the mixture, and $K_2$ is a constant which depends on the entrainment velocity and the burning rate of mass, $m_1$, as well as on the mixture. Therefore, when the same mixture is used, $\Delta r_p$ is determined by the amount of mass, $m_1$, its entrainment velocity, and the burning rate of $m_1$.

These factors are affected by the configuration of the PJ ignitor and the discharge energy.

In regard to the configuration of the PJ igniter, the characteristic penetration depth of the plasma jet, $L^*$, is proposed by Cetege et al.:

$$L^* = V_p / A$$

where $V_p$ is the cavity volume and $A$ is the flow area of the discharge orifice. The characteristic length of the PJ igniter, $L^*$, and the discharge energy, $E$, are thought to be the factors affecting $m_1$ and $K_2$. Therefore, $\Delta r_p$ for the same mixture is considered to be a function of $L^*$ and $E$, however, the relation among $L^*$, $E$, $m_1$, and $K_2$ is not known yet, so $\Delta r_p$ is described as a function of $L^* E$ (Fig. 11). From Fig. 11, $\Delta r_p$ correlates well with $L^* E$, and $\Delta r_p$ increases with an increase in the value of $L^* E$. Its effect is larger in the leaner mixtures.

From the above combustion model, we assumed that $\Delta r_p$ is independent of the combustion vessel volume, however, the effect of combustion vessel appears in Fig. 11. This result indicates that the values of $m_1$ and $C_3$, i.e., the characteristics of the formation of the turbulent plume, are related to the combustion chamber volume; the smaller combustion chamber decreases the values of $m_1$ and $C_3$. This is probably caused by the restriction of the entrainment mass into the jet by the combustion chamber wall, and by the decrease in the jet performance due to a higher back pressure in the smaller combustion chamber during the ejection of the jet. The degree of these influences is not known yet, however, it is presumed that when the combustion vessel is larger than a certain volume, the above influences will not appear.

![Fig. 9 Relation between $\Delta r$ and $P^*$](image)

![Fig. 10 Variations of $\Delta r$ with $P^*$ (equivalence ratio=0.4, vessel I)](image)
4. Conclusions

Combustion tests of lean hydrogen-air mixtures were carried out with varying the governing parameters of PJ1, and the following conclusions were obtained:

1. The combustion enhancement by PJ1 is revealed only in the initial stage of combustion, and after that the combustion is similar to "Normal" ignition.

2. A comparing parameter for the performance of PJ1, especially in its initial stage of combustion where the pure performance of the jet occurred, was proposed; the amount of reduction time by PJ1 to attain the same combustion pressure rise as "Normal" ignition signifies the degree of combustion enhancement by PJ1, and is considered the comparing parameter, Δτp.

3. The comparing parameter, Δτp, is well arranged by the characteristic length of the PJ igniter, L*, and the discharge energy, E.

References


