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PROPAGATION PROCESSES OF NEWLY DEVELOPED PLASMA JET IGNITER

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ABSTRACT−In plasma jet ignition, combustion enhancement effects occur toward the plasma jet issuing direction. Therefore, when the igniter is attached at the center of a cylindrically shaped combustion chamber, plasma jet should issue toward the round combustion chamber wall. The plasma jet igniter that had an annular circular orifice has been developed. The purpose of this study is to elucidate the relationship between the newly developed plasma jet igniter configuration and combustion enhancement effects. In this newly developed plasma jet igniter, flame front wrinkle appears on the flame front and flame propagates rapidly. Plasma jet influences on the flame propagation for long period when the plasma jet igniter has issuing angle 90 degrees and large cavity volume, because the plasma jet only lasts several ms. However, in the early stage of combustion, flame front area of issuing angle 45 degrees is larger than that of 90 degrees, because the initial flame kernel is formed by the plasma jet.

KEY WORDS : Plasma jet ignition, Combustion enhancement, Issuing angle

1. INTRODUCTION

Plasma jet ignition has been investigated as an effective method for ignition and enhancement of burning velocity (Rao and Dabora, 1984; Yoshida *et al*., 1994; Wiriyawit and Dabora, 1984; Tanaka *et al*., 1998; Cetegen *et al*., 1980; Yoshida *et al.*, 1996). In the plasma jet ignition, the high voltage electrical discharge occurs from the tip of the center electrode to the edge of circular orifice, then the gas in the cavity is changed into plasma. Plasma jet issues into the combustion chamber passing through the circular orifice by the high pressure in the cavity. The high temperature plasma jet certainly ignites the lean mixture in combustion chamber. The effectiveness of plasma jet ignition for the combustion enhancement and ignition has been substantiated experimentally (Rao and Dabora, 1984; Yoshida *et al*., 1994) and theoretically (Wiriyawit and Dabora, 1984). However, the plasma jet ignition has not been put to practical use yet. Because there are two difficult problems to be solved; *i.e*. an extremely large electrical ignition energy and the erosion of electrode. Usual plasma jet ignition needs the electrical energy of several joules in order to change the gas in the cavity into plasma, so that the electrode is quickly worn by this large electrical energy. Therefore, it is very important for the practical use of plasma jet ignition to reduce the ignition energy.

In the ordinary plasma jet igniter, the plasma jet issues toward the direction of the central axis of igniter. In this study, the plasma jet igniter that has an annular circular orifice is developed (Tanaka *et al.*, 1998), as shown in Figure 1. The annular circular orifice is formed by an outer circular orifice and a round plate that is attaching to the tip of the center electrode. The plasma jet issues from the annular circular orifice and spreads toward the round combustion chamber wall. It is expected that the electrical supplied energy is effectively changed to combustion enhancement effects compared with the ordinary plasma jet igniter, and the magnitude of the electrical supplied energy could be reduced in this newly developed plasma jet igniter.

The purpose of this study is to elucidate the relationship between the newly developed plasma jet igniter configuration and combustion enhancement effects using a constant volume vessel. In the ordinary plasma jet igniter, the cavity volume and orifice area influence on the flame propagation process. Therefore, in this newly developed plasma jet igniter, the combustion enhancement effects would be also influenced by the cavity volume, outer circular orifice diameter, round plate

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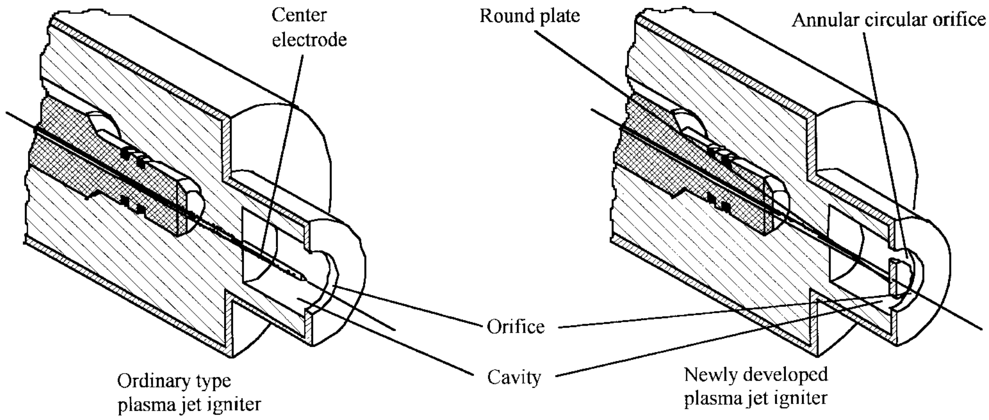

Figure 1. Newly developed plasma jet igniter and the ordinary plasma jet igniter.

diameter and the issuing angle. Combustion enhancement effects are examined by measuring the combustion pressure and visualization of the flame propagation process with various plasma jet igniters.

2. EXPERIMENTAL APPARATUS AND TEST PROCEDURE

Figure 2 shows details of plasma jet igniter. The plasma jet igniter consists of three parts: cavity that is a cylindrically shaped hole, an outer circular orifice and a center electrode that has a round plate at the tip. The thickness of outer circular orifice plate and round plate are 1 mm. The annular circular orifice is the space between an outer circular orifice and a round plate, therefore, the annular circular orifice is not only the plasma jet discharging space but also the spark discharge gap, and the difference between outer circular orifice radius and round plate radius is corresponding to the electrical discharge gap width.

Cavity diameter D is equal to the cavity depth L, and eight different cavity sizes were used; these were 5, 6, 7, 8, 9, 10, 11 and 12 mm. Eight outer circular orifice diameters d_2: these were 5, 6, 7, 8, 9, 10, 11 and 12 mm and eight round plate diameters d_1: these were 3, 4, 5, 6, 7, 8, 9 and 10 mm were used. The issuing angle is the edge angles of outer circular orifice and round plate from the igniter surface. Two plasma jet issuing angles: 45 and 90 degrees, were prepared. Four annular circular orifice widths, that is the electrical discharge gap width, were

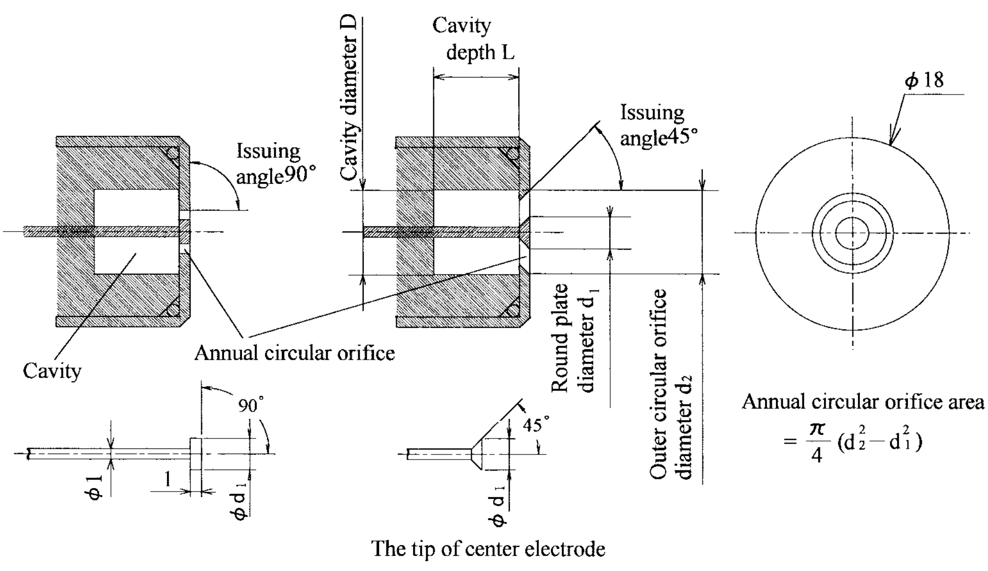

Figure 2. Details of plasma jet igniter.

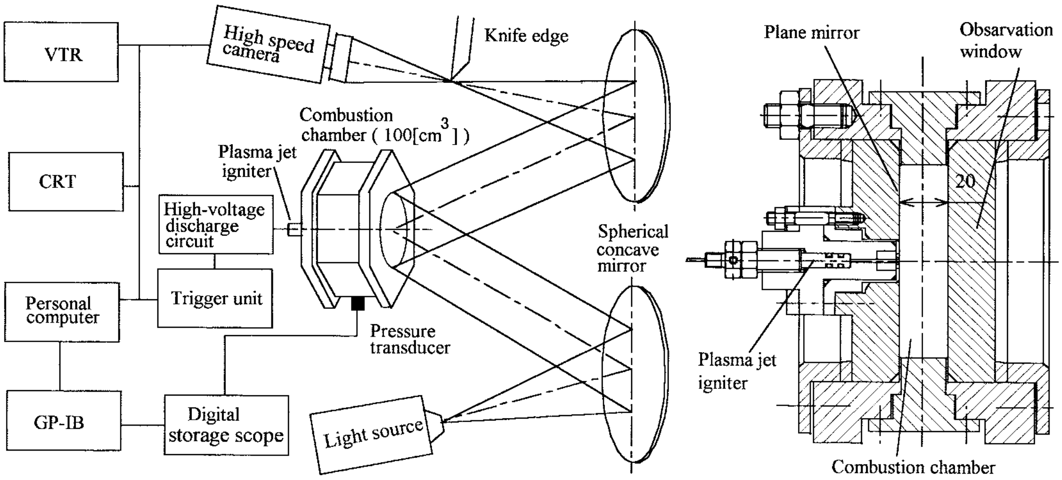

Figure 3. Schematic diagram of experimental apparatus.

used: these were 1, 2, 3 and 4 mm. Therefore, seventy different combinations of plasma jet igniter were examined for two issuing angles, because the combination of plasma jet igniter must be satisfied below condition:

Round plate diameter d_1 < Outer circular orifice diameter $d_2 \leq$ Cavity diameter D.

Figure 3 shows schematic diagram of experimental apparatus and the constant volume combustion vessel used in this study. The apparatus consists of combustion chamber, plasma jet generating system, combustion pressure measuring system and the schlieren photography system. The combustion chamber is a cylindrically shaped with 80 mm of diameter and 20 mm of thickness; its volume is about 100 cm^3. The plasma jet igniter is attached to the center of the combustion chamber. The plane mirror is fixed on the inside of the vessel for the schlieren photography system and in another side a quartz observation window is attached. The flame propagation process was visualized by the schlieren photography system and flame front area was measured at an arbitrary time from the ignition by using the image processing system. Combustion pressure was measured by the strain gage type pressure transducer. The maximum combustion pressure and burning period which was the period from the time of ignition to the time of reaching the maximum combustion pressure were analyzed from combustion pressure records. Propane-air mixture of equivalence ratio of 1.0 was used as the inflammable gas mixture. The same mixture was charged in both combustion chamber and cavity. The experiment was carried out to the mixture in the stationary state at atmospheric pressure and room temperature.

The supplied electrical energy of 5.00 J was stored in capacitance of 0.1 μF at charging voltage of 10 kV in order to generate the plasma jet. The supplied energy of 5.00 J is almost the same ignition energy as the ordinary plasma jet ignition (Rao and Dabora, 1984; Yoshida *et al*., 1994; Wiriyawit and Dabora, 1984; Tanaka *et al*., 1998; Cetegen *et al*., 1980; Yoshida *et al*., 1996). In the case of conventional ignition, the spark plug of which spark gap width was about 2 mm was attached in place of the plasma jet igniter and the electrical ignition energy was about 100 mJ.

3. RESULT AND DISCUSSION

Figure 4 shows flame propagation processes for four newly developed plasma jet igniter combinations and conventional ignition. The four plasma jet igniters were assembled by two different cavity sizes: 9×9 and 11×11 and two issuing angles: 45 and 90 degrees and all igniters had the same annular circular orifice: that was the outer circular orifice diameter of 6 mm and the round plate diameter of 4 mm. Here, the symbol of cavity: 9×9 denotes a cavity diameter of 9 mm and cavity depth of 9 mm. In all schlieren images, the black circle which can be found at the center of combustion chamber is the shadow of plasma jet igniter, therefore it should be neglected.

In the case of conventional ignition, a laminar flame front propagates circularly toward the round combustion chamber wall and the flame front propagates very slowly. In the case of newly developed plasma jet igniter, the flame front wrinkle appears on the flame front and the flame propagates rapidly in the initial stage of combustion compared with that of conventional ignition. In the case of issuing angle 90 degrees, flame front area is extended and flame propagation is faster than that of issuing angle 45 degrees for both igniters. In the case of issuing angle 45 degrees, the wrinkle on the flame front disappears immediately after the ignition, and the wrinkle

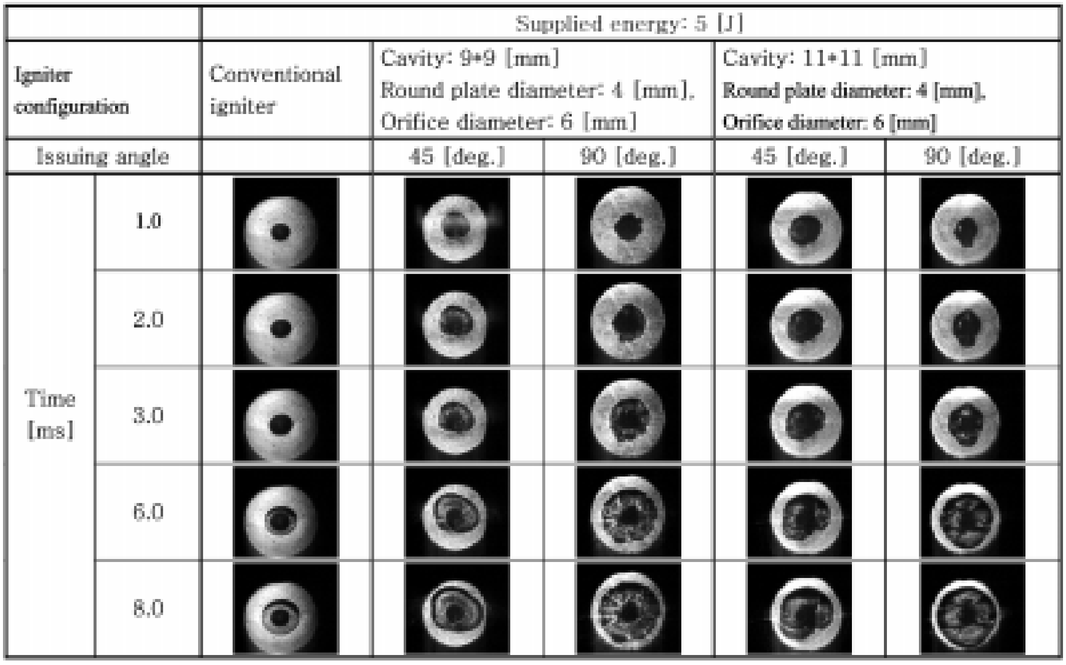

Figure 4. Images of flame propagation processes.

exists for long period when the igniter is equipped with issuing angle 90 degrees. In the case of large cavity volume: 11×11, the flame is propagating very quickly compared with that of cavity 9×9. Therefore, plasma jet influences on the flame propagation for the long period in the case where the igniter is equipped with issuing angle 90 degrees and large cavity volume.

Figure 5 shows the flame front area and the combustion pressure as a function of time after ignition for two igniters equipped with issuing angles 45 and 90 degrees and the case of conventional ignition. In the case of the conventional ignition, the combustion pressure gradually

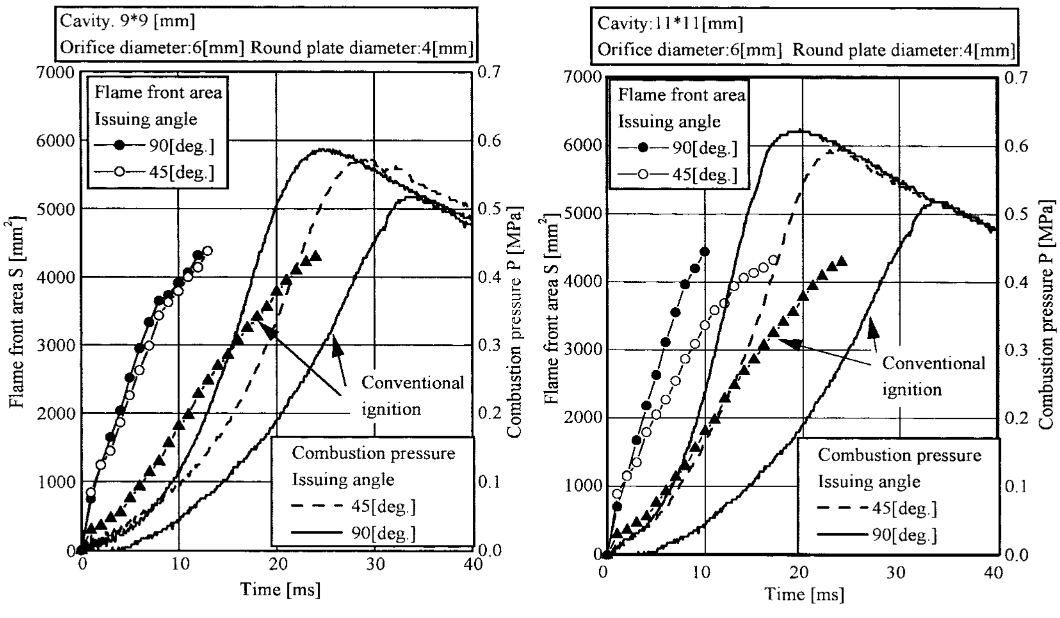

Figure 5. Flame front area and combustion pressure as a function of time after ignition.

rises until about 5 ms after the ignition, then the combustion pressure linearly increases as the time passage. The maximum combustion pressure of about 0.52 MPa is indicated at 34.8 ms after the ignition. In the case of newly developed plasma jet igniter, for both issuing angles 45 and 90 degrees and both igniters, the combustion pressure rises very rapidly immediately after the ignition and the burning period is evidently shortened compared with the conventional ignition. The large initial flame kernel created by the plasma jet causes this rapid pressure rise. The maximum combustion pressure is very larger than that of the conventional ignition. The short burning period makes the maximum combustion pressure increase, because the heat loss to the combustion chamber wall is decreased. Therefore, this newly developed plasma jet igniter certainly enhances the combustion and increases the combustion pressure.

In both igniters, the combustion pressure of issuing angle 90 degrees rises very rapidly and maximum combustion pressure increases compared with those of issuing angle 45 degrees. The maximum combustion pressure of large cavity volume: 11×11 is larger than that of small cavity volume: 9×9 and the burning period is shortened. Therefore, the plasma jet igniter configuration such as cavity volume and issuing angle influences on the combustion and flame propagation.

In the case of conventional ignition, flame front area gradually increases as similar manner to combustion pressure record. However, in the case of plasma jet ignition, flame front area is increasing immediately after the ignition. In the extremely initial stage of combustion, flame front area of issuing angle 45 degrees is slightly larger than that of issuing angle 90 degrees, however then the flame front area of issuing angle 90 degrees becomes larger than that of issuing angle 45 degrees until the combustion is completed.

Figure 6 shows relationship between flame front area which is measured at 1, 2 and 3 ms after the ignition as a function of characteristic length of plasma jet igniter. The characteristic length of the igniter is related to the entrainment of ambient gas into the plasma jet and is the representative parameter of plasma jet igniter (Cetegen *et al.*, 1980). In this study, the characteristic length of the igniter is defined as follows: characteristic length L^+ = cavity volume/annular circular orifice area. The ordinary plasma jet igniter which has a large characteristic length L^+, that is the large cavity volume and small orifice area, is favorable for the combustion enhancement.

In the extremely initial stage of combustion, 1 ms after the ignition, flame front area of issuing angle 45 degrees is larger than that of 90 degrees. For both issuing angles 45 and 90 degrees the flame front area reduces as the characteristic length increases. It is assumed that the initial flame kernel is formed by the plasma jet itself. The

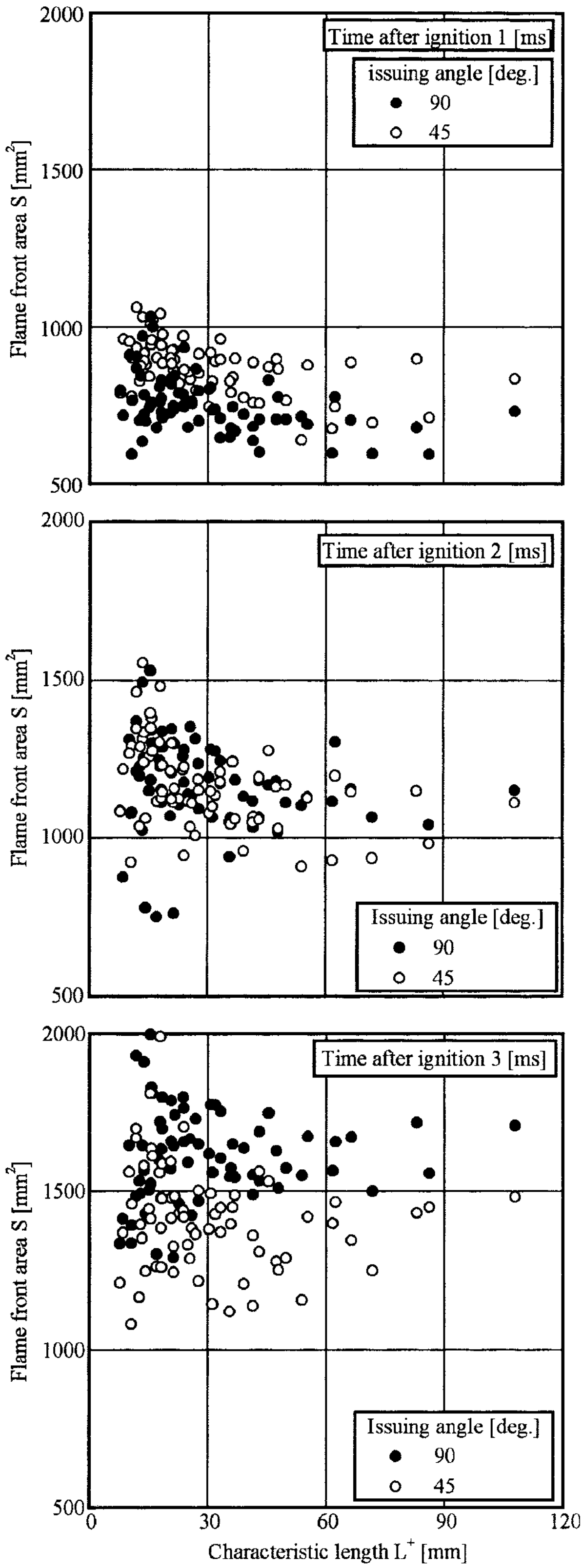

Figure 6. Relationship between flame front area at an arbitrary time after ignition and characteristic length.

diffusion of plasma jet of issuing angle 45 degrees is always slightly larger than those of 90 degrees, because the orifice effect caused by the issuing angle of 45 degrees makes the plasma jet spread (Tanaka *et al.*, 1998). Therefore, flame front area of issuing angle 45 degrees is extended by the plasma jet. The plasma jet issues from the part of annular circular orifice in the case of the plasma jet igniter of which outer circular orifice diameter is relatively large and annular circular orifice width is narrow (Tanaka *et al.*, 1998). The annular orifice width of igniter which has a small characteristic length is wide, so that the large plasma jet and large initial flame kernel is created.

In the case of 2 ms after the ignition, for both issuing angles 45 degrees and 90 degrees, flame front area gradually increases as the characteristic length of igniter becomes large. Difference between flame front area of issuing angle 45 and 90 degrees becomes indistinct. In the case of 3 ms after the ignition, the flame front area of 90 degrees is larger than that of 45 degrees and is increasing with an increase of the characteristic length of igniter. This is because the plasma medium: that is the mixture in the cavity, is increased with increasing the cavity volume and the orifice effect also increases as annular circular orifice area becomes small. This is the same feature as the ordinary plasma jet igniter. The flame front area of 90 degrees becomes larger than that of 45 degrees. It is assumed that the hot gas jet which issues after plasma jet have finished issuing influences on the flame propagation (Yoshida *et al.*, 1996). The hot gas jet is ejected by the high temperature and high pressure gas remained in the cavity, and the hot gas jet also affects the combustion enhancement effects. When the igniter equipped with issuing angle 45 degrees, the annular orifice area of inside cavity (the inlet of the annular orifice) is smaller than the outside annular orifice area, as shown in figure 2. If the hot gas jet is choked at the inlet of annular orifice, amounts of the hot gas jet decreases compared with that of issuing angle 90 degrees. The velocity of hot gas jet will be reduced because the orifice area is gradually extended. Therefore, the flame propagation velocity becomes slow in the case of issuing angle 45 degrees.

Figure 7 shows combustion enhancement ratio ψ, maximum combustion pressure P_{max} and index of combustion I_c' as a function of characteristic length of the igniter with issuing angle 45 degrees and 90 degrees. The combustion enhancement ratio is defined by the ratio of the burning period of the plasma jet ignition t_{pl} to that of the conventional ignition t_{con}. The combustion enhancement ratio is expressed by the following equation (Yoshida *et al.*, 1994):

$$\psi = 1 - t_{pl}/t_{con}$$

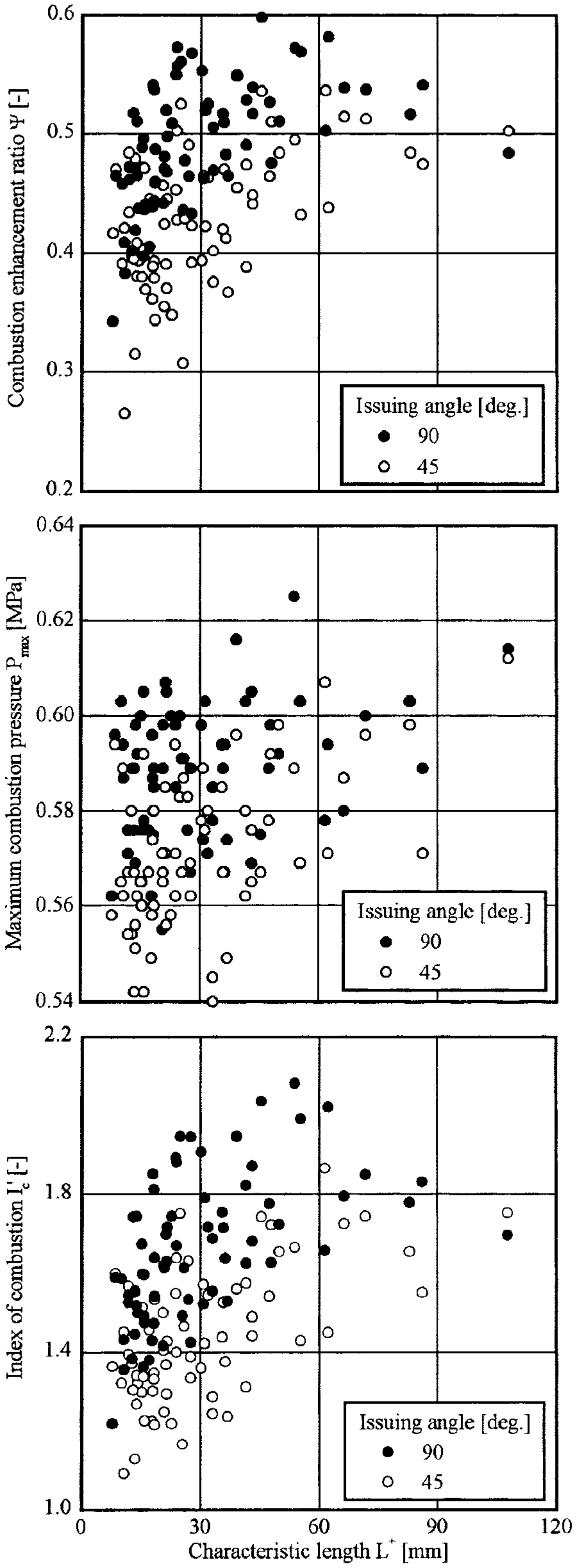

Figure 7. Combustion enhancement ratio, maximum combustion pressure and index of combustion as a function of characteristic length.

The combustion enhancement effect increases as the combustion enhancement ratio approaches 1. The index of combustion was introduced by Rao Mittinti *et al*. (1984) in order to evaluate the performance of plasma jet igniter. The ordinary index of combustion was the product of the combustion efficiency (as measured by the ratio of the actual peak pressure rise to theoretical peak pressure) and non-dimensional burning period (actual burning period to the theoretical burning period which is calculated from the laminar flame speed). We defined the index of combustion I_c' using the maximum combustion pressure P_{con} and burning period t_{pcon} of conventional ignition instead of theoretical peak pressure and burning period, and the index of combustion I_c' in this study was defined as follows:

$$I_c' = (P_{max}/P_{con})/(t_{pmax}/t_{pcon})$$

The combustion enhancement ratio, maximum combustion pressure and index of combustion of issuing angle 45 degrees are always lower than those of 90 degrees.

In the case of the issuing angle 45 degrees, it is assumed that the plasma jet and initial flame kernel propagate along the combustion chamber wall, so that the heat loss to the combustion chamber wall is increased.

In both issuing angles 45 and 90 degrees, the maximum combustion pressure increases as the characteristic length of the igniter increases. The combustion enhancement ratio shows almost the same tendency as the maximum combustion pressure. Basically, the index of combustion in this study is the product of maximum combustion pressure and the combustion enhancement ratio; therefore, the index of combustion also increases as the characteristic length of the igniter increases. The performance of this newly developed plasma jet igniter is in the same manner as the ordinary plasma jet igniter and the plasma jet igniter which has a large characteristic length is favorable for the combustion enhancement and the rise of combustion pressure. Therefore, in the early stage of combustion, the initial flame kernel is extended by the igniter which has a small characteristic length, however the igniter of large characteristic length indicates an effective combustion enhancement for combustion in whole combustion chamber.

4. CONCLUSIONS

(1) In newly developed plasma jet igniter, flame front wrinkle appears on the flame front and flame propagates rapidly. In the case of issuing angle 90 degrees, flame propagation is faster and flame front wrinkle exists for longer period than that of issuing angle 45 degrees. Plasma jet influences on the flame propagation for long period when the igniter equipped with issuing angle 90 degrees and large cavity volume.

(2) In the extremely initial stage of combustion, 1 degrees after the ignition, flame front area of issuing angle 45 degrees is larger than that of 90 degrees because the initial flame kernel is formed by the plasma jet. Then flame front area of issuing angle 45 degrees becomes smaller than that of 90 degrees.

(3) In the extremely early stage of combustion, the initial flame kernel is extended by the igniter which has a small characteristic length, however the igniter of large characteristic length indicates an effective combustion enhancement for combustion in whole combustion chamber.

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