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40 A Study on Diffusion Combustion Induced by High-Voltage Spark

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New diffusion combustion that is induced by high-voltage spark is proposed. In this method, the electrical discharge is given to the liquid fuel in cavity of igniter. The purpose of study is to elucidate the influence of igniter configuration and the charged fuel volume on the diffusion flame, and the combustion is observed in the open atmosphere. The diffusion flame development process is divided into two parts: those are the periods affected by the fuel injection and the buoyancy. When the air is included in the cavity, the diffusion flame exists for a long period because the combustion is similar to the partially premixed combustion.

Keywords: Engine Combustion / Diesel Engine, Diffusion Combustion, High-Voltage Electrical Discharge

1. INTRODUCTION

In the premixed combustion of a spark ignition engine, an operation with a very lean mixture is effective in reducing exhaust gas emission of pollutants and enhancing thermal efficiency. However, it is necessary to ensure a certain ignition and to increase the burning velocity. For the diffusion combustion of a compression ignition engine, the diesel knock will occur when the ignitability of fuel is inferior. [1] Then, many investigations of new concept combustion for the internal combustion engines have been studied, such as HCCI combustion [2] and AR combustion [3]. In this study, a new concept of combustion which is using the characteristic of plasma jet ignition is proposed. This new combustion method has features of both premixed and diffusion combustion and improves the disadvantage of both combustion processes.

In the procedure of plasma jet ignition [4], a high-voltage electrical discharge is generated from the tip of the center electrode to the edge of circular orifice and then the gas in the cavity is transformed to a plasma state. This high-temperature plasma jet spreads into the combustion chamber and can ignite a lean mixture better than a regular spark plug ignition. When the cavity of the plasma jet igniter is filled with a liquid fuel, the liquid fuel is evaporated by the high-temperature plasma immediately after the electrical discharge, and then the plasma jet made from the fuel vapor spreads into the combustion chamber. The plasma jet of fuel vapor is mixed with the surrounding air in the combustion chamber, and diffusion combustion occurs. This new concept of diffusion combustion, that is the diffusion combustion induced by high-voltage spark is proposed in this study and fig. 1 shows the igniter which is used in this study.

When this new concept diffusion combustion is applied to the internal combustion engine, following points will be expected:

1) Rapid combustion: the plasma jet made from the fuel vapor includes a lot of radicals and is very high -temperature, therefore the diffusion combustion will immediately occur without ignition delay. The plasma jet made from fuel issues into combustion chamber very rapidly, so that the combustion will be completed within very short duration.
2) High compression ratio and lean combustion: the high compression ratio and lean combustion will be available because of diffusion combustion.

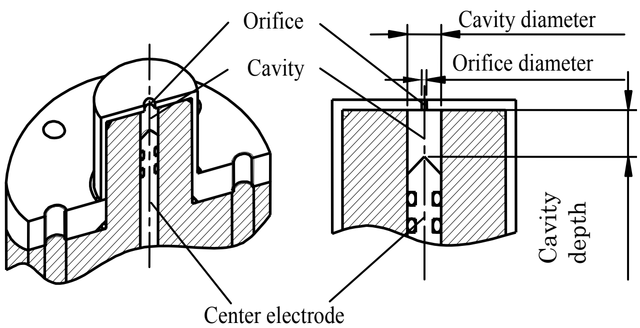

Fig. 1 Igniter.

3) Diversification of fuel: various liquid fuels such as gasoline, diesel fuel, methanol and ethanol can be burned by this diffusion combustion.

Therefore, the high thermal efficiency internal combustion engine can be realized by this new combustion method.

The purpose of this study is to elucidate the possibility of realizing the diffusion combustion induced by high-voltage spark and to clarify the characteristic of this new combustion method. Combustion experiments are carried out in the open atmosphere and the combustion feature is analyzed from the visualization of the diffusion flame development processes. Methanol that is one of alternative fuels is charged in the cavity of igniter and the fuel is spread into the air at room temperature and atmospheric pressure.

2. EXPERIMENTAL APPARATUS AND TEST PROCEDURE

Fig. 2 shows the details of igniter and dimensions. The igniter is consisted of three parts: cavity that is a cylindrically shaped hole, a circular orifice and a center electrode. Therefore, the igniter has the same component parts with the ordinary plasma jet igniter. The tip of center electrode is pointed and its angle is 90 [deg.]. The tip of electrode is the bottom of the cavity, so that the cavity volume is the space above the center electrode. The electrical discharge occurs between the tip of center electrode and the edge of circular orifice, and the thickness of orifice plate is 0.5 [mm].

Cavity diameter is always 3.3 [mm]. Four different cavity depths, L are used, these are 1, 2, 4 and 6 [mm] and three circular orifice diameters, d: 1, 2, and 3 [mm] are used. Therefore, twelve different combinations of igniter are examined in the tests.

The methanol is used as the liquid test fuel in this study because the methanol has a simple molecular structure. Methanol volume is measured by a micro syringe and is provided to the cavity through the orifice. The minimum methanol volume provided is 9 [μl] and the maximum methanol volume provided is each cavity volume. The provided methanol volumes are corresponding to 25-40, 50-65, 75 and 100 [%] of each cavity volume, because the ratio of fuel volume to cavity volume influences on the ignition probability and diffusion flame development. [5]

Fig. 3 shows a schematic diagram of experimental apparatus. The experimental apparatus consists of the igniter, the capacitance high voltage discharge circuit and the schlieren system with a high-speed camera. The igniter is set toward the vertically upward direction and the fuel is ejected into the open atmosphere. The surrounding air is at room temperature and atmospheric pressure, and the experiments are carried out in the stationary surrounding air condition.

The diffusion combustion process is visualized by the conventional Z shape schlieren system in order to make clear the fuel spray condition and combustion. The maximum height which can be observed by this schlieren system is about 220 [mm]. To take the schlieren images, the high-speed camera is used and images are taken by 2000 [frame/s] and the shattering speed is set by 1/40000 [s]. The schlieren images taken are analyzed by using the image processing system and the binary image

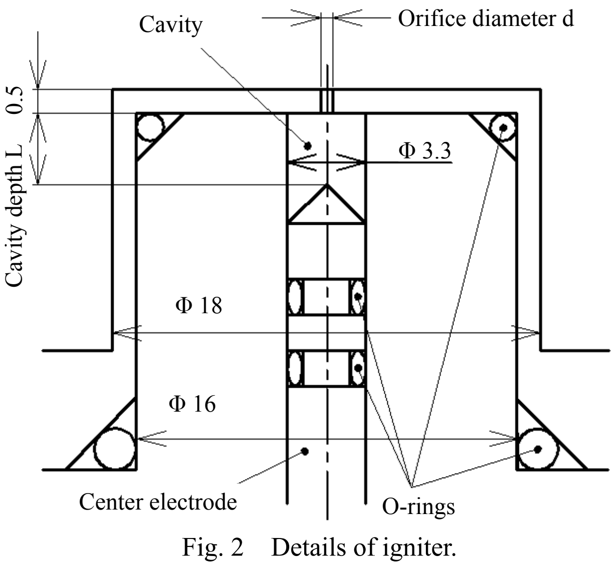

Fig. 2 Details of igniter.

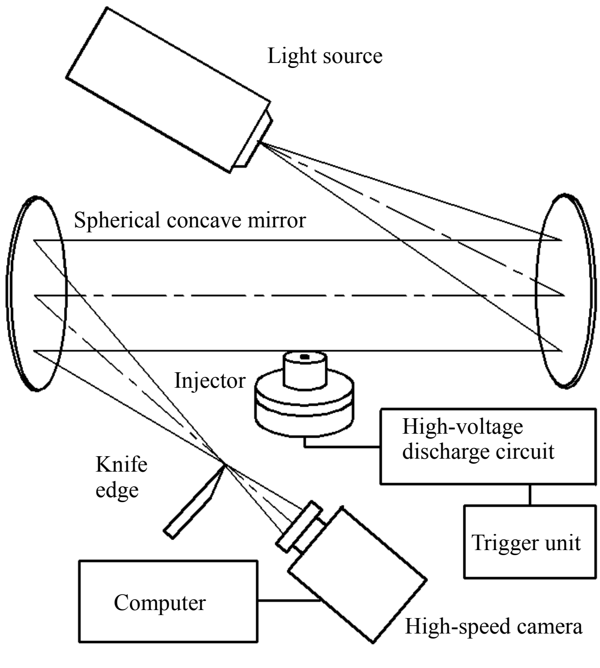

Fig. 3 Schematic diagram of experimental apparatus.

analyzing method is applied. The top position of diffusion flame and flame projection area are measured at an arbitrary time from the electrical discharge.

The capacitance high-voltage discharge circuit is used and the negative high voltage is stored in the capacitance in order to discharge easily. The supplied electrical energy of 5 [J] is stored in capacitance of 0.1 [μF] at the charging voltage of -10 [kV] and this electrical discharge energy is almost equal to the ordinary plasma jet ignition [4]. The high-voltage electrical discharge is completed within about 40 [μs].

3. RESULTS AND DISCUSSION

Table 1 indicates experimental results of the occurrence of diffusion combustion for various igniter combinations and fuel volumes. The occurrence of diffusion combustion is judged by the visual observation. In fig. 4, the ignition processes and initial stage of combustion are conceptually illustrated.

In cases at which small cavity volume (cavity depth of 1 [mm]) is used and the cavity is fully filled with the fuel, the diffusion combustion is certainly observed. However, for small cavity volume, when a small amount of fuel is charged in the cavity, the diffusion combustion is not observed. It can be assumed, as illustrated in the case of the small cavity volume of fig. 4, the plasma jet issued from the igniter ignites the fuel droplets and mixture which is ejected from the igniter. Therefore, when the small amount of fuel is only charged in the cavity, the fuel-air mixture will be generated in cavity and issues from the orifice by the electrical discharge, however the mixture is too lean to initiate the diffusion combustion. When the cavity is fully filled with the fuel, the mixture is rich enough to burn and the diffusion combustion can occur, so that the mixture is immediately ignited at the outside of igniter and the diffusion combustion can continue by the ejected fuel droplets.

In cases at which large cavity volume is used and the fuel corresponding to the half of cavity volume is provided, the diffusion combustion is certainly observed. However, if the cavity is almost filled with the fuel, the diffusion combustion is not occurred and the fuel droplets are ejected from the igniter in similar to the fuel injector of diesel engine. It can be thought, as illustrated in fig. 4, the diffusion combustion begins inside the cavity, therefore the mixture preparation and ignition is simultaneously occurred by the electrical discharge in the cavity. The fuel droplets which are ejected by the high-pressure in the cavity are successively burned and

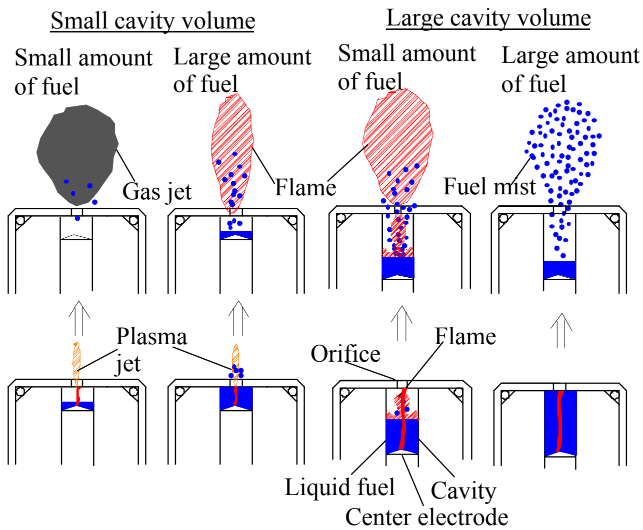

Fig. 4 The conceptual figures of the initial stage of combustion after the discharge.

Table 1 Experimental results.

Cavity depth	Orifice diameter	Fuel volume / Cavity volume							
		25 – 40 [%]		50 – 65 [%]		75 [%]		100 [%]	
1 [mm]	1 [mm]	-	-	9 [μl]	Extinguishment	-	-	18 [μl]	Combustion
	2 [mm]		-		Extinguishment		-		Combustion
	3 [mm]		-		Extinguishment		-		Combustion
2 [mm]	1 [mm]	9 [μl]	Combustion	18 [μl]	Combustion	20 [μl]	Extinguishment	27 [μl]	Extinguishment
	2 [mm]		Combustion		Combustion		Combustion		Combustion
	3 [mm]		Combustion		Combustion		Combustion		Combustion
4 [mm]	1 [mm]	18 [μl]	Combustion	27 [μl]	Extinguishment	33 [μl]	Extinguishment	44 [μl]	Extinguishment
	2 [mm]		Combustion		Combustion		Extinguishment		Extinguishment
	3 [mm]		Combustion		Combustion		Extinguishment		Extinguishment
6 [mm]	1 [mm]	15 [μl]	Combustion	30 [μl]	Extinguishment	46 [μl]	Extinguishment	61 [μl]	Extinguishment
	2 [mm]		Combustion		Extinguishment		Extinguishment		Extinguishment
	3 [mm]		Combustion		Extinguishment		Extinguishment		Extinguishment

the diffusion combustion continues. When a lot of fuel is provided and few air remains in the cavity, the fuel is not ignited and the fuel droplets are only ejected from the igniter by the high-pressure.

Fig. 5 shows the examples of diffusion combustion processes and the case of fuel injection for two orifice diameters of 1 and 2 [mm]. The cavity depth of 2 [mm] is selected because the diffusion combustion occurs with few exceptions.

The diffusion combustion is apparently occurred by this combustion method, and the diffusion flame is spread and is developed as the provided fuel volume increases at an arbitrary time from the injection. In the case of fuel volume 9 [μl], the diffusion flame does not fully grow and the combustion is completed within about 30 [ms]. This is because the enough fuel droplets to maintain the diffusion combustion is not included in the flame.

Until about 10 [ms] after the electrical discharge, the diffusion flame grows keeping the spherical shape, and then the flame shape is changed and the flame is enlarged toward the upward direction. Therefore, the diffusion flame development process can be divided into two parts. In the first period that is the fuel injection affected period, fuel droplets and fuel-air mixture which are ejected by the electrical discharge strongly influences on the diffusion combustion, so that the diffusion flame keeps the spherical shape and the whole flame rapidly moves upward by the fuel injection velocity. In the second period that is the buoyancy affected period, the fuel injection has been already completed and the buoyancy of flame influences on the flame itself, so that the flame can not hold the spherical shape and is stretched toward upward. The flame gradually rises by the buoyancy.

In the case of orifice diameter of 1 [mm], the diffusion combustion can not be generated although an enough fuel is supplied for a small cavity volume. It can be considered that the plasma jet can not be ejected from the orifice, because the electrical discharge energy is absorbed by the cooling loss of the very narrow orifice area and the evaporation of large amount of fuel. Until about 10 [ms] after the electrical discharge, the fuel injection development process is almost similar to that of the diffusion flame.

Fig. 6 shows the top position of diffusion flame and flame projection area as a function of time after electrical discharge. The top position of flame is measured from the end of igniter to the highest position of diffusion flame at an arbitrary time from the electrical discharge until the

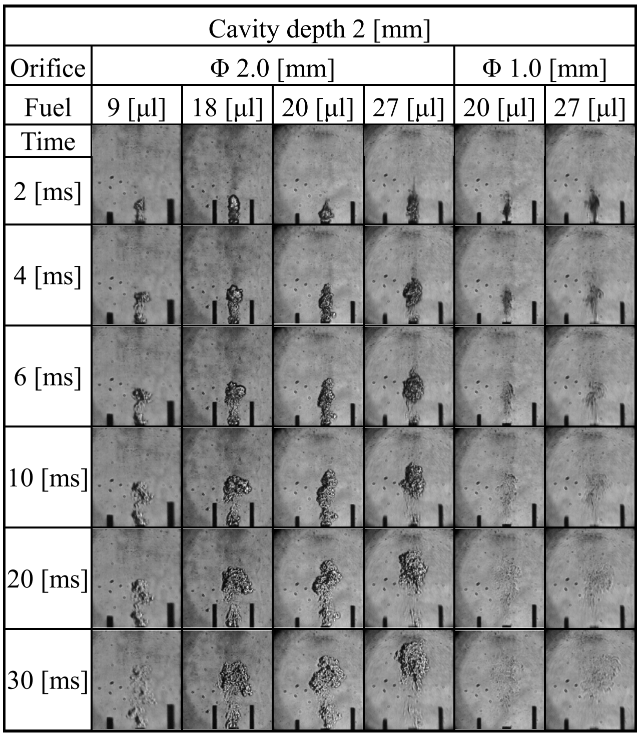

Fig. 5 Time series images of diffusion combustion and fuel injection.

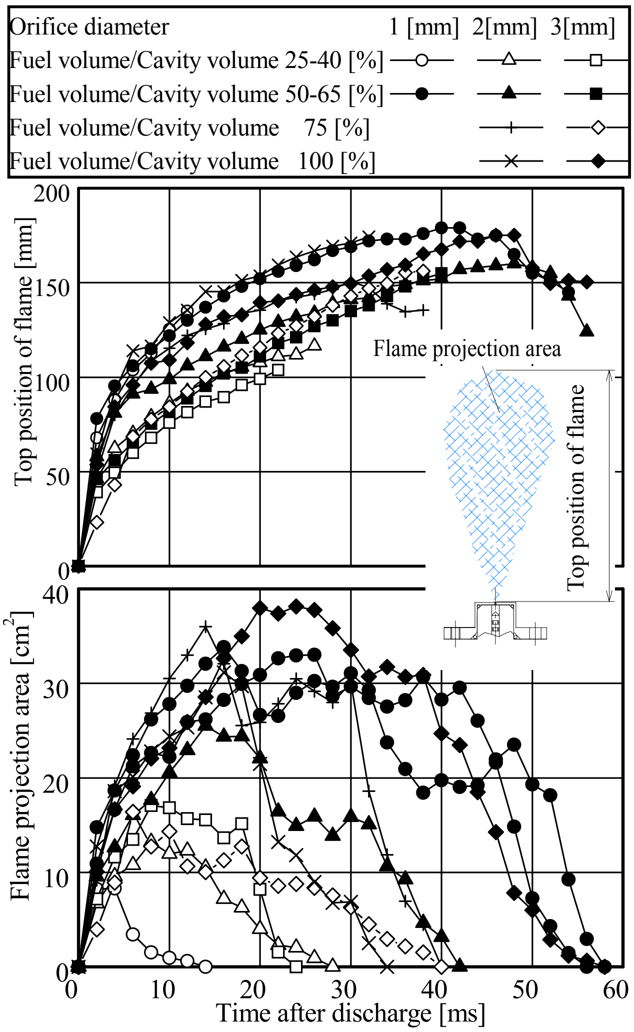

Fig. 6 Top position of diffusion flame and flame projection area as a function of time after discharge.

diffusion flame disappears. The flame projection area is also measured at an arbitrary time from the electrical discharge and the diffusion flame extension can be evaluated from the flame projection area.

The top position of flame is increasing as the time elapses and is gradually decreasing after the peak value is shown. The flame projection area is also increasing and decreases rapidly after the maximum value is shown, because the ejected fuel is burned. Both top position of flame and flame projection area increase and the diffusion combustion continues for a long period as the ratio of fuel volume to cavity volume increases because the provided fuel increases. Both top position of flame and flame projection area increase as the orifice diameter decreases due to the orifice effect.

The top position of flame rapidly increases until about 10 [ms] after the electrical discharge and then the increasing tendency becomes less steep because the flame raises by the buoyancy. In the case at which the ratio of fuel volume to cavity volume is about 50 [%], the diffusion flame is existing relatively long period compared with other cases. It is assumed that the combustion process is similar to the partially premixed combustion because the appropriate air volume to make fuel-air mixture is included in the cavity.

Fig. 7 shows the time at which the maximum flame projection area is indicated and the maximum flame projection area as a function of characteristic length of igniter L^+. Here, the characteristic length of igniter L^+ is used for the plasma jet igniter and is defined in equation (1). The characteristic length is related to the entrainment of ambient gas into the plasma jet and is the representative parameter of plasma jet igniter. The plasma jet igniter which enhances the combustion effectively has a large characteristic length L^+. [4]

$$\text{Characteristic length } L^+ = \text{Cavity volume / Orifice area} \qquad (1)$$

The time at which the maximum flame projection area is indicated shifts to early stage and the maximum flame projection area decreases as the provided fuel volume decreases because the diffusion combustion is early completed. The time at which the maximum flame

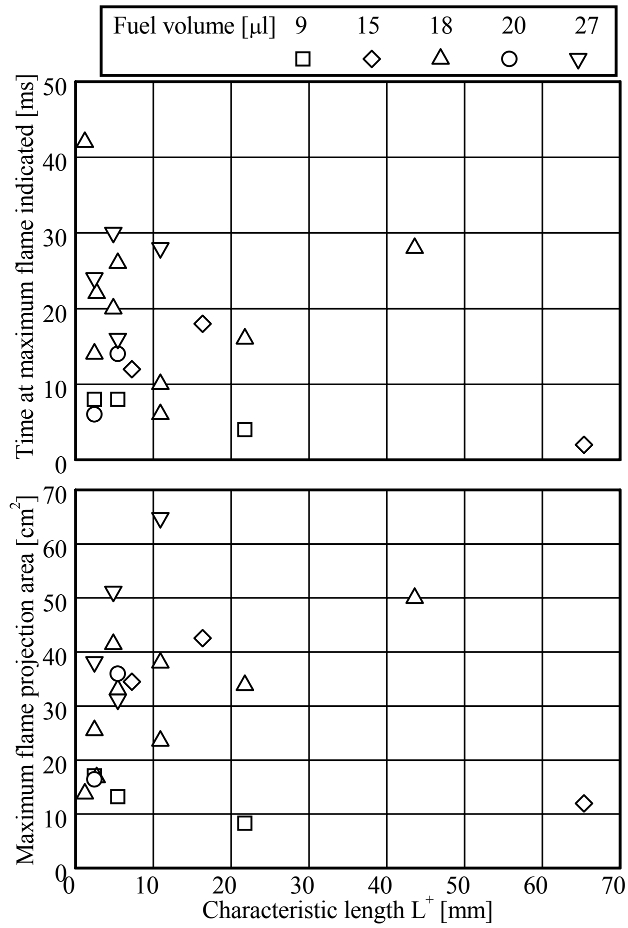

Fig. 7 Time at which the maximum flame projection area is indicated and the maximum flame projection area as a function of characteristic length of igniter.

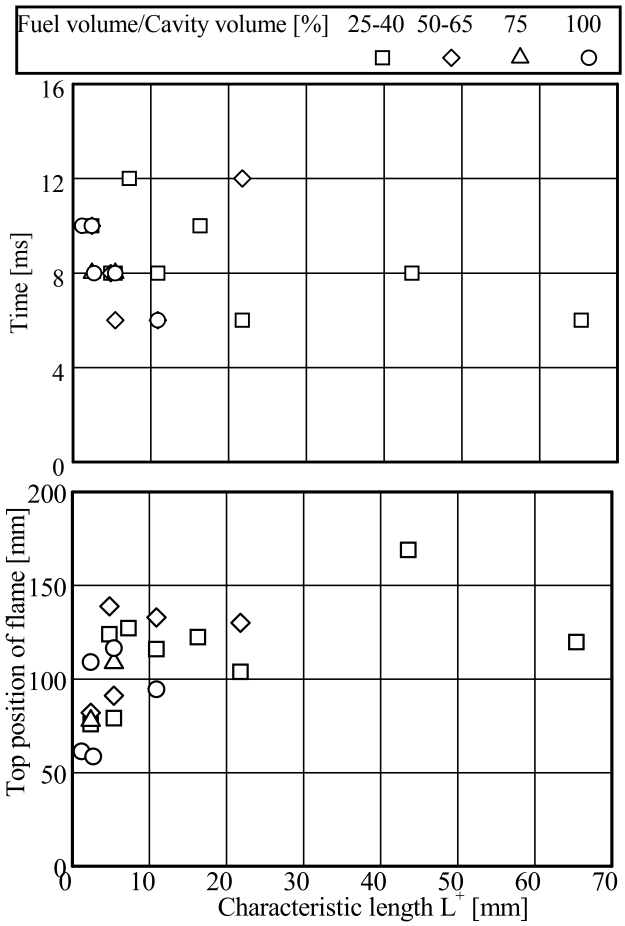

Fig. 8 Time and top position of flame when the influence on diffusion flame is changed from the fuel injection to the buoyancy as a function of characteristic length of igniter.

projection area is indicated shifts to early stage as the characteristic length becomes large even though the same fuel volume is supplied. It is seemed that, for the igniter of large characteristic length, the entrainment of surrounding air into the diffusion flame is enhanced in similar way to the plasma jet ignition.

Fig. 8 shows the time and top position of flame when the influence on diffusion flame is changed from the fuel injection to the buoyancy, as discussed in fig. 5, as a function of characteristic length of igniter. The time is determined by the increasing tendency of top position of flame indicated in fig. 6.

The time when the influence on diffusion flame is changed from the fuel injection to the buoyancy becomes early and the flame top position at that time becomes high as the characteristic length increases regardless of the ratio of fuel volume to cavity volume. It is seemed that the development process of ejected fuel mist and fuel-air mixture is very similar to that of the plasma jet. This suggests that the initial stage of diffusion combustion which is affected by the fuel injection is promoted by the igniter of large characteristic length. Therefore, it can be concluded, from figs. 7 and 8, the igniter which has a large characteristic length is suitable for the diffusion combustion induced by high-voltage spark.

Fig. 9 shows the mean velocities of flame top of both fuel injection affected period and buoyancy affected period as a function of characteristic length of igniter. The mean velocity of flame top is defined as the inclination of liner approximation equation which is obtained from the relationship between top position of

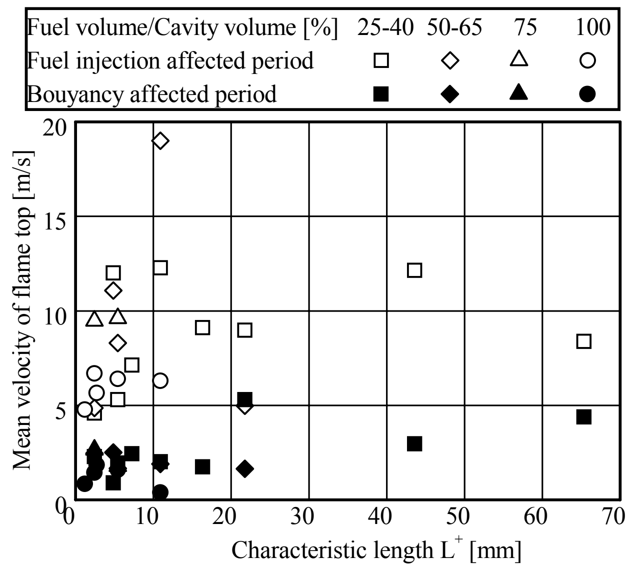

Fig. 9 Mean velocities of flame top of the fuel injection affected period and a buoyancy affected period as a function of characteristic length of igniter.

flame and elapsed time shown in fig. 6. The fuel injection affected period and a buoyancy affected period are divided at the time indicated in fig. 8.

In any cases, the mean velocity of flame top of the fuel injection affected period is faster than that of buoyancy affected period, therefore the diffusion combustion induced by high-voltage spark is enhanced in the initial stage of combustion. Both mean velocities of flame top of fuel injection affected period and buoyancy affected period are increasing as the characteristic length increases. Therefore, the igniter of large characteristic length makes the diffusion flame velocity fast.

4. CONCLUSIONS

(1) In cases of small cavity volume, the plasma jet can ignite the fuel outside of the igniter. In cases of large cavity volume, the diffusion combustion is initiated inside the cavity, and when the cavity is almost filled with the fuel, the fuel droplets are only ejected.
(2) The diffusion flame development can be divided into two parts: the first period is affected by the fuel injection and the second period is influenced by the buoyancy.
(3) When the air is included in the cavity, the diffusion flame exists for a long period because the combustion process is similar to the partially premixed combustion.
(4) The igniter which has a large characteristic length is suitable for this diffusion combustion because the entrainment of surrounding air into the diffusion flame is enhanced. The diffusion combustion is especially enhanced in the initial stage of combustion.

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