# Fundamental Study on the Radical Ignition Technique Using Constant Volume Chamber (CVC)

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*Abstract:* - A previous fundamental study was executed using a constant volume chamber (CVC) to improve the burning characteristics of lean pre-mixture by the injection of active radicals generated in the sub-chamber of the CVC. The Radical ignition (RI) technique shows remarkable progress in the burning velocity and combustible lean limit compared with spark ignition (SI) technique. And the optimum design value of the sub-chamber geometry is near $0.11\text{cm}^{-1}$ in the ratio of total area of holes to the sub-chamber volume ($A_h/V_s$). In this study, based on the previous experimental study, the additional works have been performed to examine the effects of geometry change in the number ($N_h$), the total section area ($A_h$), and diameter ($D_h$) of the passage holes on the combustion characteristics in the CVC. A single frame ICCD camera was used for the measurement of CH and $C_2$ radical distribution in the combustion chamber. Also, ambient conditions such as the initial temperature and the initial pressure of mixture were selected as experimental parameters. As a result, the correlation between passage hole number and overall passage hole area was grasped. The effects of initial temperature were significant, but on the other hand, those of initial pressure were weak.

*Key-Words:* - Radical ignition, Sub-chamber, Passage hole, Lean burn, Constant volume chamber, Combustion

## 1 Introduction

We intended to develop a so-called radical ignition technique (RI method) that tries to improve the combustion characteristics of lean mixture by installing the sub-chamber over the main chamber. This burning method is distinguished from that of the existing gasoline engine. The flame kernel generated by the spark ignition method (SI method) grows into an autogenous flame and relies on the subsequent flame propagation. In the RI method, the rapid combustion is realized by the ejection of burning products created in the sub-chamber, that is, the high-temperature products injected into the main chamber through numerous passage holes enhances the ignitability of the mixture owing to high energy density and various kinds of active radicals. Also the multi point auto-ignition and the expansion of the early flame front due to the live turbulence enables the lean mixture to burn rapidly in the main chamber.

Higelin et al. [1] and Ma et al. [2] reported that the demerit of low combustion velocity of lean combustion can be overcome by radical injection with high energy level at the sub-chamber because the radicals ejected from the sub-chamber rapidly induce the sure ignition of lean mixture at the main-chamber.

In this study, the basic experiments on radical injection technique were performed for data acquisition needed to the application into an actual engine by using a CVC (Constant Volume Chamber). This study based on the results of the previous study was minutely executed for the effects of the number of the passage hole, total area of the holes, diameter of the holes, and the ambient conditions such as the initial temperature and the initial pressure of on the combustion characteristics of the lean mixture.

## 2 Experimental Apparatus and Conditions

### 2.1 Experimental Apparatus

Fig. 1 shows the schematic diagram of the experimental apparatus, which consists of the CVC divided into a main chamber (Diameter =110mm, Height=48.5mm) and a sub-chamber, intake and exhaust parts, fuel supplying system, heating system, an DLI ignition device, pressure measuring instruments (Kistler Co, 6051B piezoelectric pressure transducer & 5011 amplifier), an ICCD camera, and a micom (PIC16C74) built-in electronic control system. The equivalence ratio of the mixture in the sub and main chamber is determined by governing a GDI injector. Also the circular quartz windows were installed on both sides of the CVC for visual measurement of radicals from sub-chamber and combustion flame at the main chamber. The detailed explanation for the experimental method is also found in results of Park et al. [3].

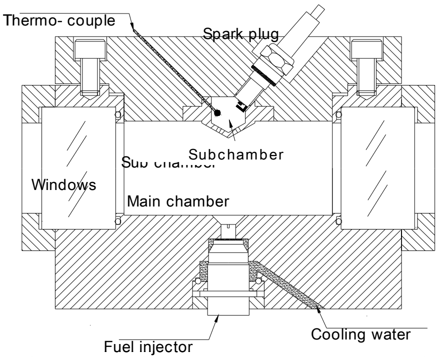


Fig. 1 Schematic diagram of experimental apparatus with constant volume combustion chamber

Fig. 2 shows the diagram of optical measurement apparatus for radicals. A single frame ICCD camera was used for the measurement of CH and $C_2$ radical distribution. And, the luminescence images from excited CH and $C_2$ radicals in the flame were measured under the same experimental condition using each band pass filter having a central wavelength of 430.2nm with a half width of 3nm for CH and a central wavelength of 518nm with a half width of 3nm for $C_2$.

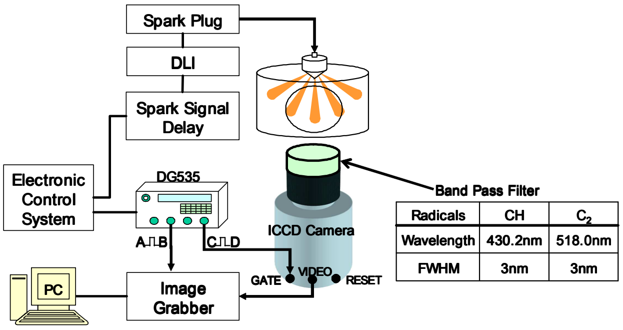
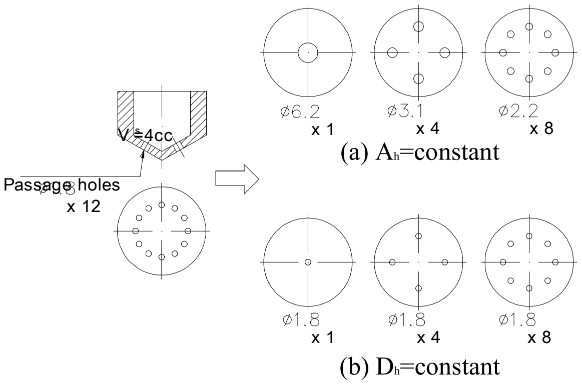


Fig. 2 Diagram of optical apparatus for radical measurement

## 2.2 Experimental Conditions

Additional experiments based on the previous study were executed for the case of the $V_s$(Sub-chamber volume)=4cc, $N_h$(Number of the passage hole)=12, and $D_h$ (Diameter of the passage hole)=1.8mm(Sum of sectional area of total passage hole, $A_h$=30.5mm$^2$) because the geometrical profile of the sub-chamber affects greatly combustion characteristics [4].

The experimental study process on the effect of the change in the geometrical profiles on the combustion characteristics can be divided into 2 stages as shown in Fig. 3. Firstly, the number ($N_h$) and diameter ($D_h$) of the passage hole were changed under the constant total-section area of the passage hole($A_h$=30.5mm$^2$) as the Fig.3-(a). Secondly, the number ($N_h$) and total-section area ($A_h$) of the passage hole were changed under the constant diameter ($D_h$) of the passage hole as the Fig.3-(b).



(a) $A_h$=constant

(b) $D_h$=constant

Fig. 3 Variation of $N_h$, $D_h$, and $A_h$ for the sub-chamber of $V_h$=4cc, $N_h$=12 and $D_h$=1.8mm

And the effects of the ambient conditions such as the initial temperature and the initial pressure of mixture were investigated. Table 1 shows the summarized ambient conditions.

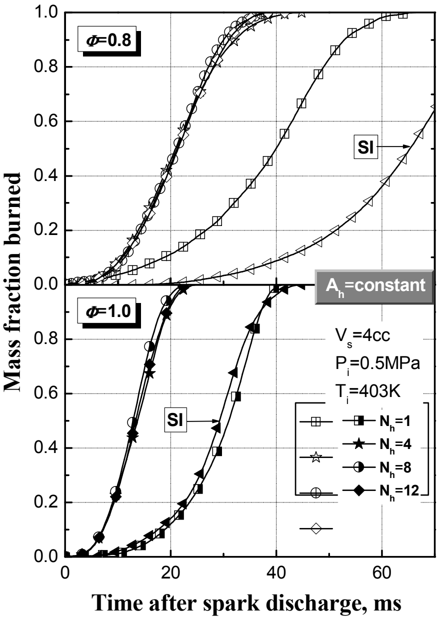
Table 1 Experimental parameter for the effect of ambient condition

| Parameters | Initial conditions |
|---|---|
| Initial temperature($T_i$) | 383, 403, 423K |
| Initial pressure($P_i$) | 0.3, 0.5, 0.7MPa |
| Equivalence ratio(Φ) | Lean limit, 0.8, 1.0 |
| Sub-chamber | $V_s$=4cc, $D_h$=1.8mm, $N_h$=12 |
| Fuel | n-heptane($C_7H_{16}$) |

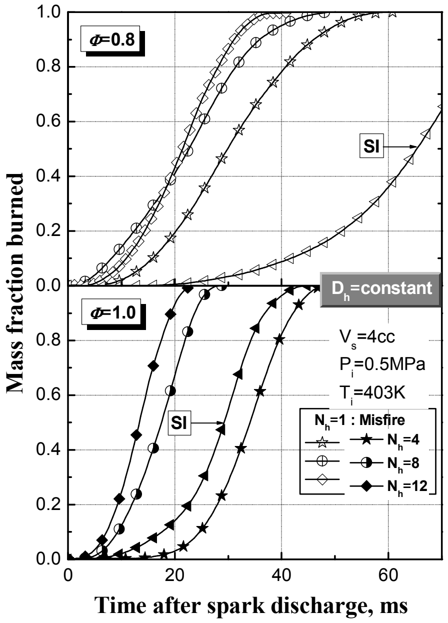
## 3 Results and Discussion

### 3.1 Effects of $N_h$, $D_h$, and $A_h$ on the Combustion Characteristics

Fig. 4-(a) shows mass fraction burned after changing the number of passage holes and fixing the total cross section of the passage holes ($A_h$=30.5mm$^2$) under the conditions of $V_s$=4cc, $N_h$=12, and $D_h$=1.8mm. Fig. 4-(b) shows mass fraction burned after changing the number of passage holes and fixing the diameter of the passage holes ($D_h$=1.8mm). Both of them were examined to grasp the simultaneous effects of the $N_h$, $D_h$, and $A_h$ of passage holes. In Fig. 4-(a), combustion period is shorter than that of the SI method in the case of single hole. The combustion period, however, is longer than that of other conditions because a large area of the single hole makes slow jet velocity from the sub-chamber decreasing turbulence strength and concentrating ignition point in one spot. However, in the other cases, except for the single hole case, it shows improved results compared with the SI method regardless of equivalence ratio. When the sub-chamber has 4 or more holes, similar combustion characteristics occurs if $A_h$ is the same. As shown in Fig. 4-(b), combustion period increases as $A_h$ decreases even if the experiments were carried out with a sub-chamber having 4 or more holes. Thus, it is proved that a critical area to the number of the passage holes exists when the sub-chamber has 4 or more passage holes.



(a) $A_h$=constant=30.54mm$^2$



(b) $D_h$=constant=1.8mm

Fig. 4 Mass fraction burned with the number of passage holes in $A_h$=C and $D_h$=C

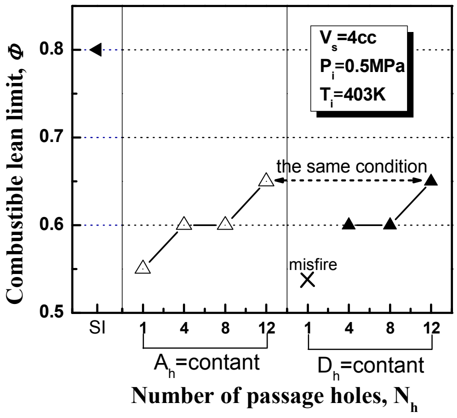


Fig. 5 Effects of passage hole number and passage area on lean combustible limit

Fig. 5 shows lean combustion limit with the change in the number and sectional area of passage hole. As the number decreases, the lean limits expand regardless of Ah because of a high concentration of jet products and a weak turbulence of mixture, which is advantageous for the formation of the initial flame. However, the main and overall burning time after that increases because of turbulence and the reduction of the initial flame surface. As we have seen, this study has been conducted for the purpose of reducing the whole combustion period and expanding the lean limit. However, it is necessary to clarify the reason of misfire occurring in a main chamber as shown in Fig. 4-(b). When a sub-chamber has identical volume and geometry in each condition, it was considered that the misfire depends on the total cross section decided by the diameter, number, arrangement, length of the holes, and so on. When the passage hole number was changed to 2 and 3 under =1.0, $D_h$=1.8mm, and the initial conditions of Fig. 4-(b), misfire happened in the main chamber. The misfires also occurred in the cases of $L_h$=2.0, 1.5, and 1.0mm. Therefore, it is considered that normal combustion is possible in cases of 4 or more holes and the length of the hole has not a lot of effects on combustion within the range of this study. Also, an experiment varying the diameter of hole from 3.6mm to 6.2mm was carried out with fixing the number of passage holes as one. $D_h$=3.6mm is corresponded to the total cross section ($A_h$=10.2mm$^2$) which is identical area with four holes of 1.8mm diameter in Fig. 3-(b).

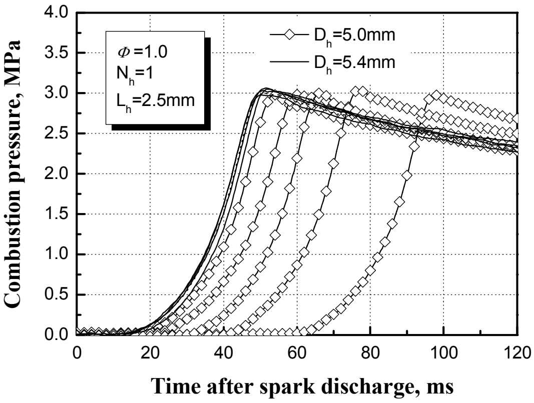


Fig. 6 P-t diagram for $D_h$=5.0mm and $D_h$=5.4mm in the case of $N_h$=1

Fig. 6 shows combustion pressure curves measured 5 times in a main chamber after spark discharge at $D_h$=5.0mm, $D_h$=5.4mm, and $N_h$=1. As shown in this figure, there is little variation in pressure for $D_h$=5.4mm while there is much irregular combustion pressure for $D_h$=5.0mm. This phenomenon took place analogously in the cases of $D_h$=4.0mm and 4.2mm, and the misfire was observed two or three times in every ten times. Thus it means that the reliable hole diameter for ignition is around 5.4mm for a single passage hole.

Fig. 7 shows the combustion pressure curves of a main chamber obtained with changing the diameter of a single hole from 3.6mm to 6.2mm. In cases below $D_h$=5.0mm, it is impossible to average the pressure because of severe variation in pressure, so that this figure represents curves close to the average of Pmax. The case of $D_h$=3.6mm was misfired. In the others, the $P_{max}$ decreases and the maximum pressure increases slightly as $D_h$ increases. However, it is shown that there is no significant variation for $P_{max}$ and the maximum pressure over $D_h$=5.8mm. A slope of main combustion period, that is, pressure increasing rate (dP/dt), shows no large variation. It is considered that the effect of ignition delay(ID) is larger than that of the other combustion periods for $P_{max}$. In the case of one hole as mentioned above, it has a longer combustion period than multi-holes because of misfire and extended ignition delay. Therefore, it is proved that one hole is a disadvantageous method compared with the SI method.

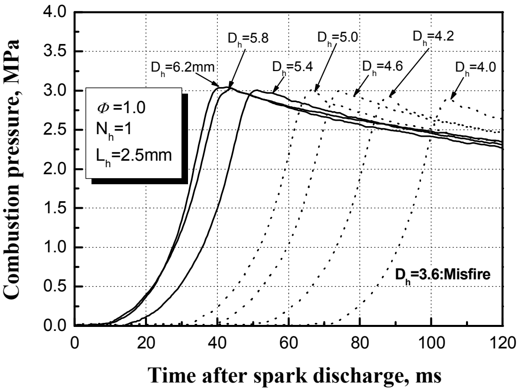
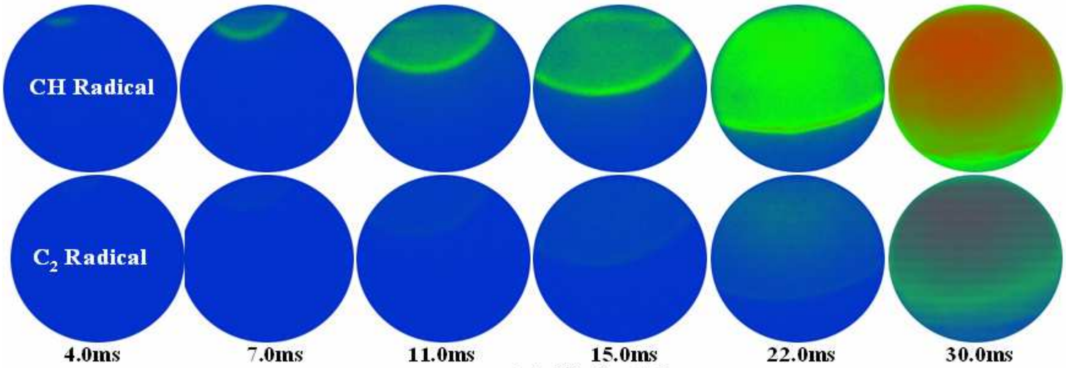


Fig. 7 P-t diagram with $D_h$ in the case of $N_h$=1

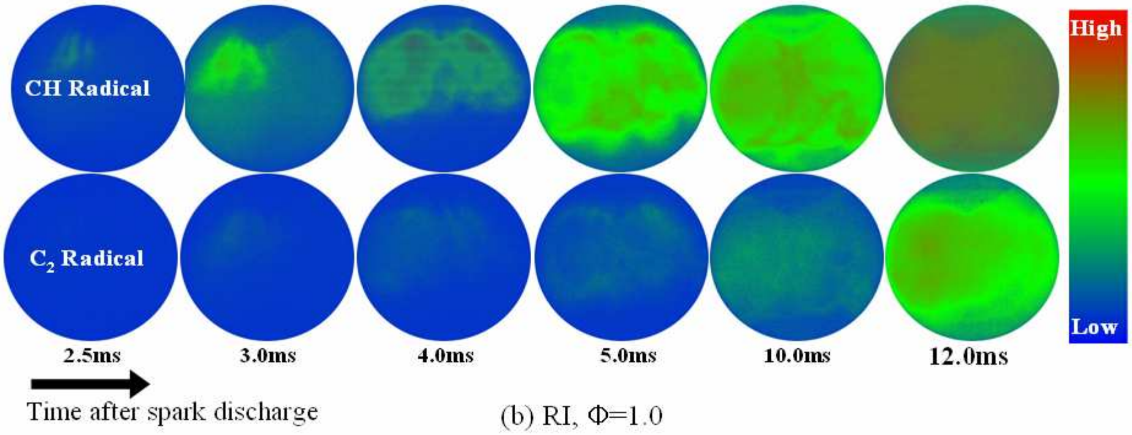
## 3.2 Visualization of CH and $C_2$ Radicals

Fig. 8 shows the radical distribution in the main chamber after spark discharge by using a single frame CCD camera with an image intensifier for SI and RI under Φ=1.0 methods. In the case of SI method, it is known that the luminescence intensity of CH radical appears strongly at the spherical main reaction zone and is generally a little weaker than the flame luminosity having a similar property in distribution to that of the flame. On the other hand, $C_2$ radical is observed after the middle period of combustion and mostly comes out in the burned zone.

In the case of RI method under Φ=1.0, the self-emission of CH and $C_2$ radicals has a wide distribution over the entire combustion chamber increasing with the elapsed time. Besides, it can be understood that the reaction rate is much higher because $C_2$ radical mainly generated in burned gas assumes a clear aspect more quickly in comparison with that of SI.



(a) SI, Φ=1.0



(b) RI, Φ=1.0

Fig 8. CH and $C_2$ Radical distribution in the main chamber after spark discharge

### 3.3 Effects of Ambient Conditions

Fig. 9 shows the effects of $T_i$ on mass fraction burned under the $P_i$=0.5MPa at the sub-chamber with $V_s$=4cc, $D_h$=1.8mm, and $N_h$=12. The initial temperature was increased from 383K to 423K at an interval of 20K. Also, Fig. 10 shows the effects of $P_i$ on mass fraction burned under $T_i$=403K at the same sub-chamber. Both of them were examined under equivalence ratio($\varphi$ )= 1.0 and 0.8.

According to the increase of $T_i$, the combustion velocity increases in combustion field. The combustion period increases regularly under stoichiometric air-fuel ratio with the decrease of the initial temperature. However, the combustion period under $\varphi$ =0.8 increases with irregularly large gaps as the initial temperature decreases. Thus it appears that the RI method depends on the ambient temperature in lean air-fuel ratio more than in the stoichiometric air-fuel ratio as shown in Fig. 9.

From the results of change in the initial pressure, the combustion period increases with the increase of pressure as in the past studies [5]. However, it is shown that the combustion period shows a slight difference, about 3% in Fig. 10.

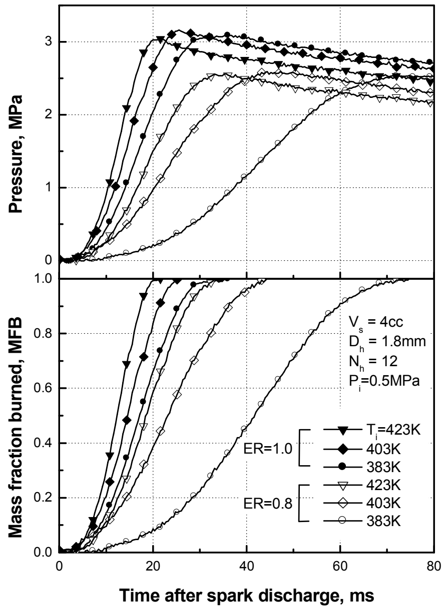


Fig. 9 Effects of initial temperature on mass fraction burned

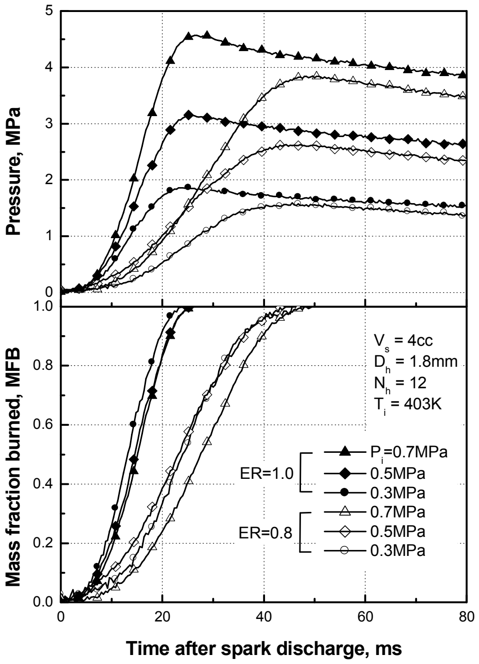


Fig. 10 Effects of initial pressure on mass fraction burned

# 4 Conclusion

An experimental study on the combustion characteristics of the RI method was performed for data acquisition needed to the applying into an actual engine by using a CVC. The effects of geometric profile (number and area of the passage hole) of the sub-chamber on the combustion characteristics were investigated. A single frame ICCD camera was used for the measurement of CH and $C_2$ radical distribution in the combustion chamber. And the initial temperature and pressure in the mixture were selected as experimental parameters. The conclusions are as follows.

1) In the case of changes in $N_h$ and $D_h$ at constant $A_h$, combustion duration with a single hole sub-chamber is much longer than that of other multi-holes. On the other hand, combustion-pressure curves with sub-chamber having 4 or more holes were almost identical regardless of equivalence ratio. Therefore, it is proved that the critical sectional area exists related to the number of passage holes. In the case of changing $N_h$ and $A_h$ at constant $D_h$, each combustion duration is in inverse proportion to $A_h$.

2) According to decrease in the number of $N_h$, the combustible lean limit expands while combustion velocity becomes slower gradually. It can be concluded that the lean limit and combustion velocity are in a trade-off relationship.

3) In the case of SI method, the luminescence intensity of CH radical appears strongly at the spherical main reaction zone and is generally a little weaker. $C_2$ radical is observed after the middle period of combustion and mostly comes out in the burned zone. In the case of RI method under $\Phi$=1.0, the self-emission of CH and $C_2$ radicals has a wide distribution over the entire combustion chamber increasing with the elapsed time.

4) The effects of initial temperature were significant, but on the other hand, those of initial pressure were weak.

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