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RADICAL IGNITION TECHNIQUE IN A CONSTANT VOLUME CHAMBER

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ABSTRACT–A prior 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 the results of the spark ignition (SI) technique. The optimum design value of the sub-chamber geometry is near 0.11 cm^{-1} for the ratio of the total area of the holes to the sub-chamber volume (A_h/V_s). In this study, based on the former experimental results, the additional works have been performed to examine the effects of the 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. Also ambient conditions such as the initial temperature and the initial pressure of the mixture were selected as experimental parameters and the effects of residual gas at the chamber on the combustion characteristics were investigated. As a result, the correlation between the passage hole number and overall passage hole area was grasped. The effects of the initial temperature were significant, but on the other hand, those of the initial pressure were weak. A more detailed analysis on the residual gas is required in the future.

KEY WORDS : Radical ignition, Sub-chamber, Passage hole, Lean burn, Constant volume combustor, Residual gas

1. INTRODUCTION

In this study, emission products formed from combustion processes at a sub-chamber were injected into a main-chamber through passage holes. Namely, in this study, the combustion process passes through 2 stages: one stage involves combustion by a spark ignition at sub-chamber and one involves combustion products ejected from the sub-chamber at main-chamber. Higelin *et al.* (1999) and Ma *et al.* (2001) reported that the demerit of low combustion speed of lean combustion can be overcome by radical injection with a high energy level at the sub-chamber because the radicals ejected from the sub-chamber rapidly induce the sure ignition of a lean pre-mixture at the main-chamber. Therefore, in this study, a basic experiment was performed for the data acquisition needed to apply the radical injection technique to actual engine operation by using a CVC (Constant Volume Chamber). This study, based on the results of a previous study was minutely executed for the effects of the number of passage holes, the total area of the holes, diameter of the holes, the initial temperature and the initial pressure of mixture, and the concentration of residual gas at the chamber on the combustion characteristics of the lean mixture.

2. EXPERIMENTAL APPARATUS AND CONDITIONS

2.1. CVC (Constant Volume Chamber)

Figure 1 shows a section view of the constant volume combustor used in this study. The CVC is made of aluminum alloy (AL7075) with cylindrical shape. The diameter and height of the CVC are 110 mm and 48.5 mm, respectively. The sub-chamber was installed at the top of the main chamber. Also, the circular quartz windows were installed on both sides of the CVC for visual measurement of radicals from the sub-chamber and the combustion flame at the main chamber. The detailed explanation for the experimental method is also found in the results of Park *et al.* (2004).

2.2. Experimental Conditions

An additional experiment based on the previous study (Chung *et al.*, 2002; Park *et al.*, 2006) was executed for the case of the V_s (Sub-chamber volume)=4 cc, N_h (Number of the passage hole)=12 and D_h (Diameter of the passage

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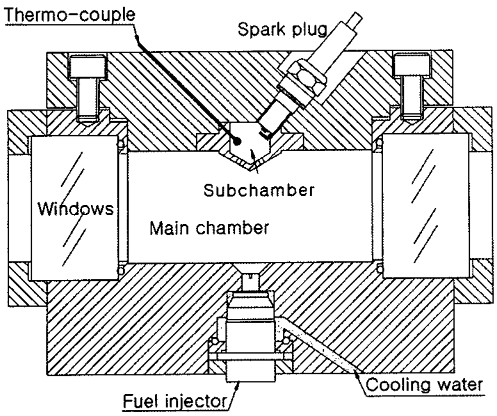


Figure 1. Schematic diagram of the experimental apparatus with a constant volume combustion chamber.

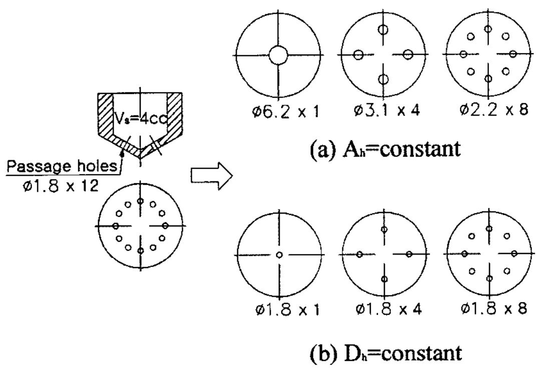


Figure 2. Variation of N_h, D_h, and A_h for the sub-chamber of V_h=4 cc, N_h=12 and D_h=1.8 mm.

hole)=1.8 mm (Sum of sectional area of total passage hole, A_h=30.5 mm^2) because the geometrical profile of the sub-chamber affects greatly the combustion characteristics.

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 Figure 2. First, the number (N_h) and diameter (D_h) of the passage hole were changed while the constant total-section area of the passage hole was held constant (A_h=30.5 mm^2) as in Figure 2(a). Secondly, the number (N_h) and the constant total-section area (A_h) of the passage hole were changed for a constant passage hole diameter (D_h) as in Figure 2(b).

Table 1 shows the parameters for the effects of the ambient conditions. The initial pressure and ambient temperature in the CVC were selected as the main parameters. The n-heptane (C_7H_{16}) was used in this study. The equivalence ratio of the mixture in the main chamber and sub-chamber was set as the conditions of the lean flammability limit, lean region and stoichiometric air-fuel ratio region.

The problem of the scavenging residual gas remained

Table 1. Experimental parameters for the effects of the ambient conditions.

Parameters	Initial conditions	Residual gas
Initial temperature (T_i)	383, 403, 423 K	403 K
Initial pressure (P_i)	0.3, 0.5, 0.7 MPa	0.3MPa+α
Equivalence ratio (Φ)	Lean limit, 0.8, 1.0	1.0
Concentration of residual gas (δ)	0	0, 7.3, 11.2, 13.6, 20.1, 24%
Sub-chamber	V_s=4 cc, D_h=1.8 mm, N_h=12	
Fuel	n-heptane	

at the sub-chamber must be solved in 2-stage combustion system with the main and sub-chamber. Therefore, the effects of the concentration control of the residual gas on the combustion characteristic were investigated in the CVC. The geometric properties of the sub-chamber were V_s=4 cc, N_h=12 and D_h=1.8 mm and the initial temperature and equivalence ratio were constantly kept as 403 K and 1.0, respectively.

According to the concentration of the residual gas, the initial pressure (P_i) was calculated by the below equation.

$$P_i = 0.3\ \text{MPa} + \alpha \tag{1}$$

Here, 0.3 MPa is the mixture pressure and α is the pressure of the residual gas. The concentration of the residual gas (δ) was calculated by Equation (2) and changed from 0% to 24%.

$$\delta = \frac{\text{Weight of residual gas}}{\text{Weight of fuel-air mixture} + \text{Weight of residual gas}} \times 100\% \tag{2}$$

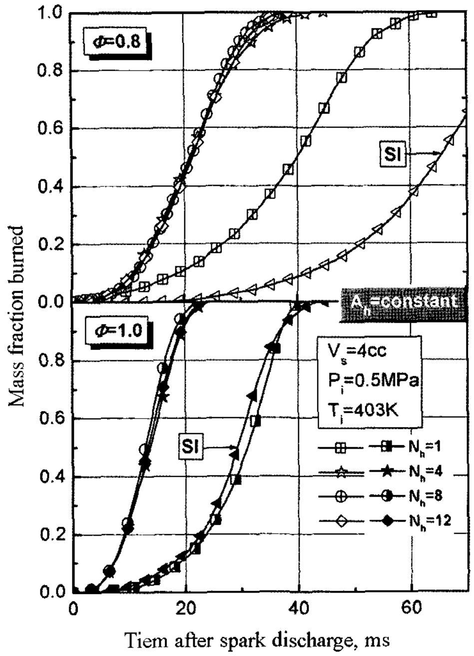
3. RESULTS AND DISCUSSION

3.1. Effects of Number and Total Sectional Area of Passage Hole on the Combustion Characteristics

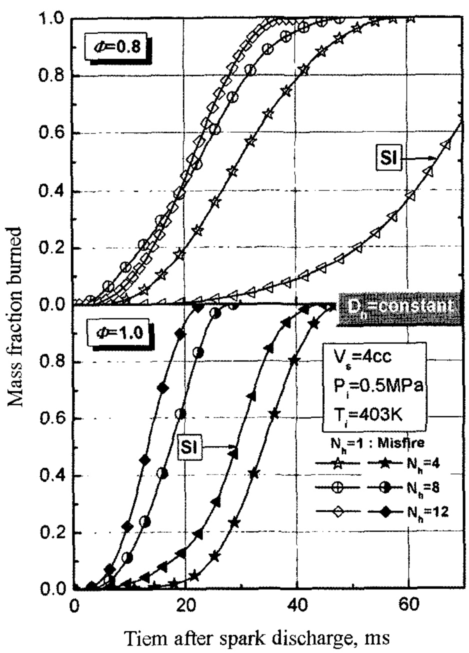
Figure 3(a) shows the mass fraction burned after changing the number of passage holes and fixing the total cross section of the passage holes (A_h=30.5 mm^2) under the conditions of V_s=4 cc, N_h=12, and D_h=1.8 mm. Figure 3(b) shows the mass fraction burned after changing the number of passage holes and fixing the diameter of the passage holes (D_h=1.8 mm). Both of them were examined to grasp the simultaneous effects of the number, the total cross section, and the diameter of the passage holes. In Figure 3(a), the combustion period is shorter than that of the SI method in the case of a single hole. The combustion period, however, is longer than that of other conditions because the large area of the single hole makes the 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 the equivalence ratio. When the sub-chamber has 4 or more holes, similar combustion characteristics occur if A_h is the same. As is shown in Figure 3(b), the 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 ratio of the critical area to the number of passage holes exists when the sub-chamber has 4 or more passage holes.

Figure 4 shows the results of the change in the combustion duration for a given number of the passage holes. The combustion duration could be measured in terms of the mass fraction burned which is obtained from the combustion pressure in the CVC. The combustion duration consists of ignition delay (τ_{ID}), flame development angle (0~10%, τ_{10}), rapid burning angle ($\tau_{90\text{-}10}$) and overall burning angle (0~90%, τ_{Pmax}), by the definition from Heywood (1988). In the case of a change in the number of passage holes kept at a constant hole diameter, all the combustion durations increase in proportion to the reduction of the number of passage holes, especially, at the stoichiometric air-fuel ratio. Then, it can be found that each combustion duration is expanded because an increase

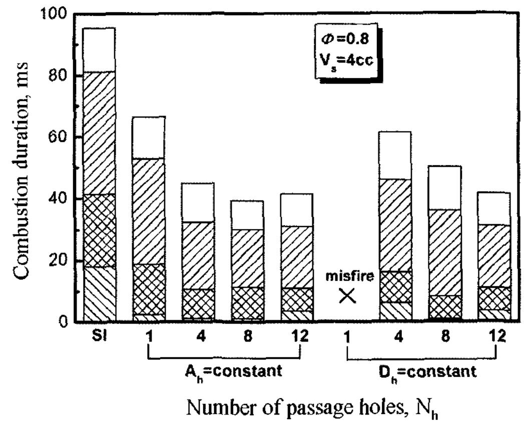


(a) A_h=constant=30.54mm^2

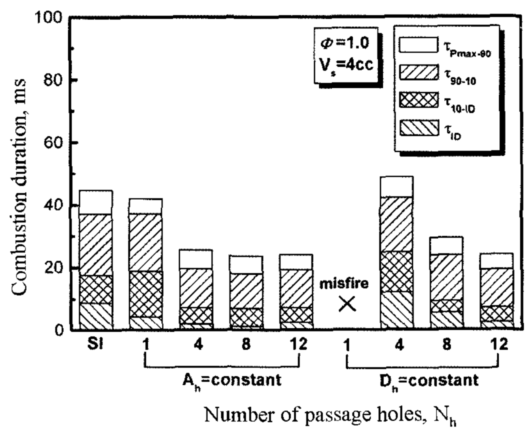


(b) D_h=constant=1.8mm

Figure 3. Mass fraction burned with the number of passage holes in cases of A_h=constant and D_h=constant.



(a) Φ =0.8



(b) Φ =1.0

Figure 4. Effects of passage hole number and passage area on each combustion duration.

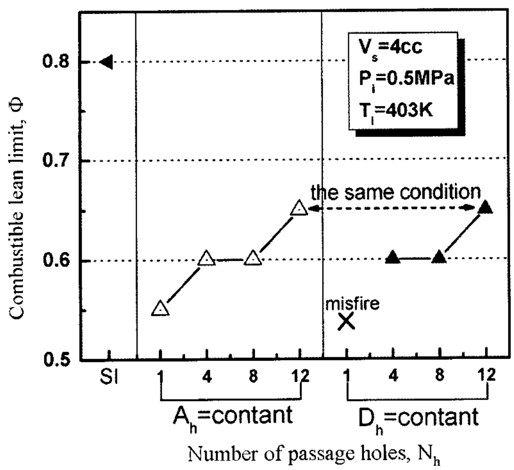


Figure 5. Effects of the passage hole number and passage area on the lean combustible limit.

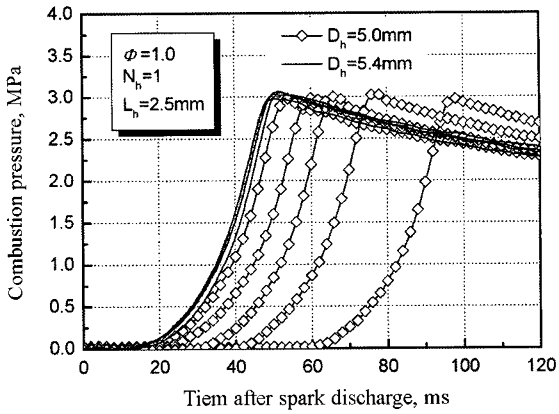


Figure 6. P-t diagram for D_h=5.0 mm and D_h=5.4 mm in the case of N_h=1.

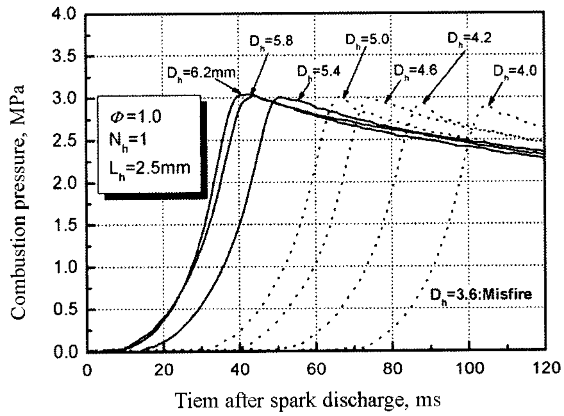


Figure 7. P-t diagram with D_h in the case of N_h=1.

in throttle loss due to the reduction of the passage hole area controls the emission ejection from the hole.

Figure 5 shows the lean combustion limit with the change in the number and sectional area of the passage hole. As the number decreases, the lean limits expand regardless of A_h because of a high concentration of jet products and a weak turbulence of the mixture, which is advantageous for the formation of the initial flame. However, the main and overall burning time after that increases because of the 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 for the misfire which occurs in a main chamber, as shown in Figure 4(b). When a sub-chamber has an 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=1.8 mm, and the initial conditions of Figure 4(b), a misfire happened in the main chamber. The misfires also occurred in the cases of L_h=2.0, 1.5, and 1.0 mm. Therefore, it is concluded that normal combustion is possible in the case of 4 or more holes and that the length of the hole does not have a lot of effect on combustion within the range of this study. Also, an experiment varying the diameter of the hole from 3.6 mm to 6.2 mm was carried out with a fixed number of passage holes (N_h=1). D_h=3.6 mm corresponded to the total cross section (A_h=10.2 mm^2) which is identical area with 4 holes of 1.8mm diameter in Figure 2(b).

Figure 6 shows combustion pressure curves measured 5 times in a main chamber after a spark discharge at D_h=5.0 mm, D_h=5.4 mm, and N_h=1. As shown in this figure, there is little variation in pressure for D_h=5.4 mm while there is an irregular combustion pressure for D_h=5.0 mm. This phenomenon took place analogously in the cases of D_h=4.0 mm and 4.2 mm, 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 5.4 mm for a single passage hole.

Figure 7 shows the combustion pressure curves of a main chamber obtained by changing the diameter of a single hole from 3.6 mm to 6.2 mm. In the cases below for D_h=5.0 mm, it is impossible to average the pressure because of severe variations in pressure, so that this figure represents curves close to the average of P_{max}. D_h=3.6 mm resulted in a misfire. 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=5.8 mm. The slope of the main combustion period, that is, the pressure increasing rate (dP/dt), shows no large variation. It is considered that the effect of the 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 for that of the multi-hole case because of the misfire and extended ignition delay. Therefore, it is proved that one hole is a disadvantageous method compared with the SI method.

3.2. Effects of the Initial Temperature and Pressure on the Combustion Characteristics

Figure 8 shows the effects of the initial temperature on the mass fraction burned under the initial pressure, P_i=0.5 MPa at the sub-chamber with V_s=4 cc, D_h=1.8 mm, and N_h=12. The initial temperature was increased from 383 K to 423 K at an interval of 20 K. Also, Figure 4 shows the effects of the initial pressure on the mass fraction burned under the constant initial temperature of T_i=403 K at the same sub-chamber. Both of them were examined under the equivalence ratios (Φ=1.0 and 0.8). According to the initial temperature increase, the combustion velocity increases in the combustion field. The combustion period increases regularly with the stoichiometric air-fuel ratio because the initial temperature decreases. Thus, the combustion period under Φ=0.8 increases with irregularly large gaps as the initial temperature decreases. Thus it appears that the RI method depends on the ambient temperature of the lean air-fuel ratio more than of the stoichiometric air-fuel ratio, as shown in Figure 8.

From the results of the change in the initial pressure,

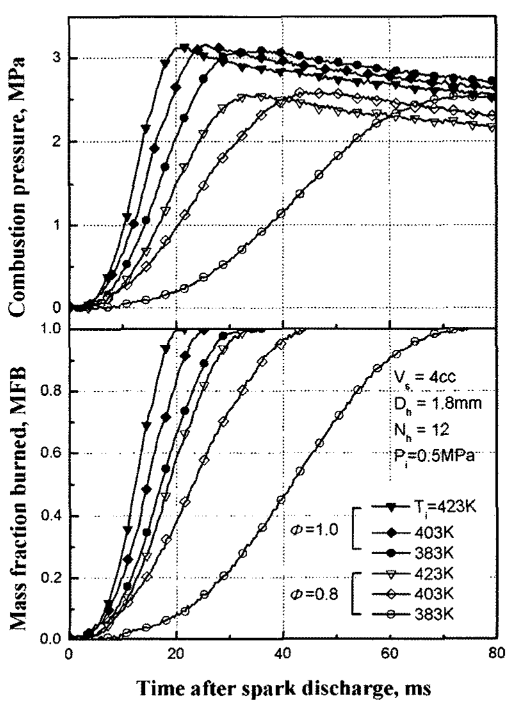


Figure 8. Effects of initial temperature on mass fraction burned.

the combustion period increases with high pressure as in the past studies (Park *et al.*, 2002). However, it is shown that the combustion period shows extremely slight differences (about 3% in Figure 9).

Figure 10 shows the effects on the lean limit of the mixture in a main chamber with a variation of the initial temperature and the initial pressure. The lean limit is decided when the mixture is burned normally over 9 times out of 10 times without misfire. It is shown that the lean limit was expanded linearly by about 0.6 as the initial temperature and initial pressure increased.

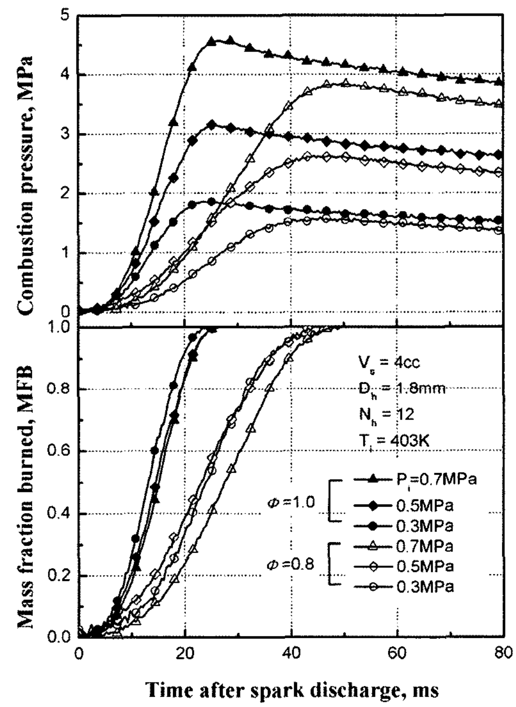


Figure 9. Effects of the initial pressure on mass fraction burned.

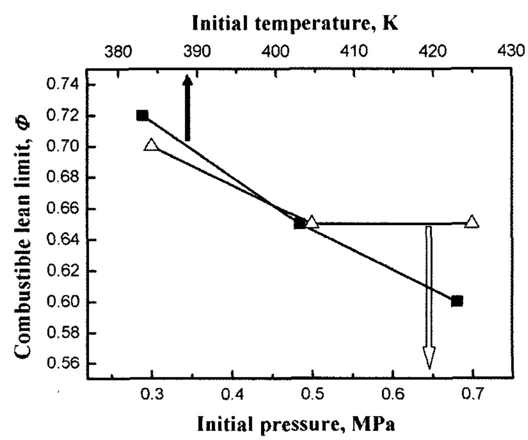


Figure 10. Effects of the initial temperature and initial pressure on the combustible lean limit.

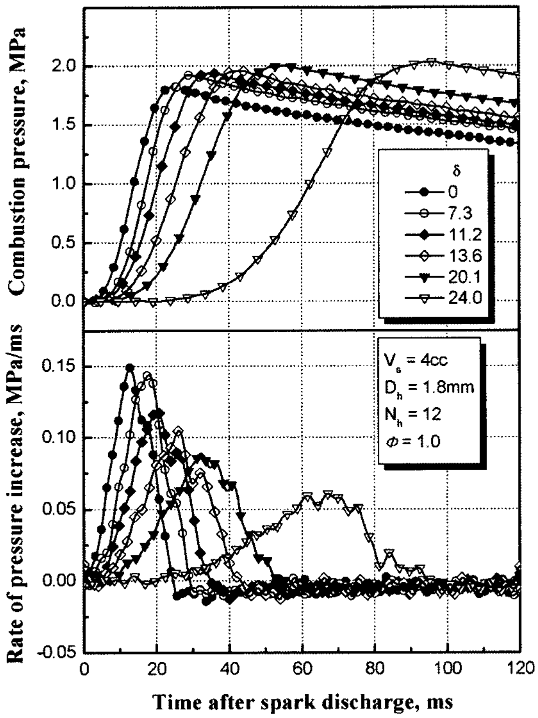


Figure 11. Combustion pressure outputs and rate of pressure increase with residual gas density.

3.3. Concentration of Residual Gas

Figure 11 indicates a diagram of pressure and the pressure increase rate for various concentrations of residual gas (δ). τ_{Pmax} increases gradually with high concentrations and reaches 96.4 ms at a concentration of 24%, which is about a four times period compared with the case of 0%. Also, the ignition does not happen in the main chamber at 30% concentration. Besides, P_{max} at δ=24% increases by about 11.5% compared with that at δ=0%, contrary to expectations. However, when the concentration of the residual gas increases, P_{max} will decrease due to the rise in heat capacity. As the result of theoretical calculations, each adiabatic flame temperature at δ=0% and δ=24% shows 9195 K and 7872 K corresponding to P_{max}=6.84 MPa and 5.86 MPa, respectively. The reason for this may be an experimental error in forming residual gas and the unburned hydrocarbon in residual gas.

4. CONCLUSIONS

An experimental study was performed of combustion characteristics using a CVC. The geometric profiles of the sub-chamber were selected as experimental parameters. Also, the effects of the initial temperature and pressure of the mixture and the concentration of the residual gas on the combustion characteristics were investigated. The following conclusions are drawn from this study.

(1) τ_{Pmax} with a single hole sub-chamber is much longer than that of other multi-holed chambers. On the other hand, the combustion pressure curves with a sub-chamber of 4 or more holes were almost identical.

(2) The lean limit and combustion velocity are in a trade-off relationship because the combustible lean limit expands while the combustion velocity becomes slower gradually according to the decrease of N_h.

(3) The effects of the initial temperature on the combustion pressure were significant, but those of the initial pressure were weak.

(4) τ_{Pmax} increased in proportion to the concentration of the residual gas by δ=24%, and misfire occurred at 30%. P_{max} increases even if the combustion period grows longer.

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