A Study on the Rapid Bulk Combustion of Premixture Using the Radical Seeding

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The objective of this study is the rapid bulk combustion of mixture in a constant volume chamber with a tiny sub-chamber. Some narrow passage holes were arranged to induce simultaneous multi-point ignition in the main chamber by jet of burned and unburned gases including radicals from the sub-chamber, and the equivalence ratios of pre-mixture in the main chamber and the sub-chamber were the same. The principal factors of the Radical Induced Auto-Ignition (RIAI) method are the diameter of the passage holes and the volume of sub-chamber. The relationship between the sub-chamber and diameter of passage hole was represented by the ratios of sub-chamber volume to passage hole volume. The ratios are non-dimensional coefficients for sub-chamber characteristics. As a result, the RIAI method reduced the combustion period, which expanded the lean limit in comparison with SI method.

Key Words: Rapid Bulk Combustion, Constant Volume Chamber, Sub-Chamber, Radical Induced Auto-Ignition method (RIAI), Lean Limit

1. Introduction

Many experimental studies on energy and stability of ignition under lean condition in an internal combustion engine have been conducted over a long period to obtain low emissions and high efficiency (Lee et al., 1996 and 1998 ; Bae et al., 1998). One of the efficient methods for emission of vehicles and improvement of specific fuel consumption is to burn lean mixture. However, the conventional lean combustion methods have problems in initial flame formation and velocity of flame propagation (Varde et al., 1995 ; Arcoumanis et al., 1994; Taro et al., 1996). In order to solve those problems, various methods to improve passive ignitability such as control of mixture flows, control of timing of fuel injection, and optimization of a geometry of combustion chamber (Kn et al., 1996 ; Edward et al., 1999) were proposed. Methods to enhance ignitability through the improvement of ignition devices (Yoshida and Saima, 1994; Heywood, 1983 ; Bae et al., 1998) were also proposed and the lean-burn technologies have been advanced from the results of the studies. The concept of rapid bulk combustion is worthy of notice as a method to compensate for limitations of usual lean-burn methods these days. The rapid bulk combustion (Lim et al., 2000) is a method that lean mixture is formed homogeneously in a cylinder and burned rapidly in the whole area of the cylinder. By using the combustion method, the velocity of flame propagation increases, so that it results in reduction of combustion period. Combustion reaction of premixture is known as a

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process that fuel and oxygen get the last combustion products through intermediate products like the active elements by many elementary reactions (Yasuhiru, 1994). Especially, the quantity of the active elements from the reactions has an effect on initial flame formation as ignition energy. Products of chain processes linking the reactions of combustion to the next chemical reaction are named Active Radicals. Higelin et al. conducted a study for realizing auto-ignition of mixture and rapid combustion by spouting combustion products including the radicals with high energy and good reactivity (Higelin et al., 1999 ; Ma et al., 2001).

In this study, as a novel combustion method using active radicals, a sub-chamber including a spark plug is installed in a constant volume chamber and combustion begins first by spark ignition in the sub-chamber. Auto-ignition is induced by charging active radicals produced from the combustion into a main chamber. In other words, combustion products produced by spark ignition in the sub-chamber are jet through several passage holes into the main chamber. The seeded radicals induce rapid chemical reactions in local area of the main chamber, so that rapid combustion occurs simultaneously in multi-spots. The volume of the sub-chamber for the Radical Induced Auto-Ignition method (which is called RIAI method hereafter) is about 1% of the main chamber and the effects of sub-chamber geometry, fuel, and combustion surroundings were studied. It was tried to find optimized conditions for stable and lean combustion by realizing rapid bulk combustion and expanding lean limit.

2. Experimental Apparatus and Methods

2.1 Experimental apparatus

Figure 1 shows the schematic diagram of the experimental apparatus, which consists of a constant volume chamber (CVC) with a main chamber and a sub-chamber, a fuel supply system, intake and exhaust devices, an electronic control system, a pressure measurement system, and a visualization system. A constant volume chamber to realize the rapid combustion of premixture by the RIAI method is shown in Figure 2. The combustion chamber is divided into both the main chamber and the sub-chamber. The main chamber is 487 cc in volume and has quartz windows to photograph luminosity of flame. The sub-chamber is attached onto the upper part of the main chamber. The volume, the number, and the diameter of passage hole are used as experimental conditions. Fuel injectors of the GDI (Gasoline Direct Injection) engines are used to form the mixture inside the sub and the main chambers. As the ignition occurs in the sub-chamber with spark discharge, burned and unburned gases including many radicals are injected into the main chamber, and then the bulk combustion of the mixture occurs. The cartridge heaters were installed in the wall of the main chamber and the sub-chamber for heating premixture and maintaining initial temperature of the combustion chamber. The K-type thermocouples of 0.1 mm diameter wire were inserted in the combustion chambers to control the temperature.

An injector which used in a GDI engine was installed to supply main and sub-chamber with forming premixture of precise air-fuel ratio. A

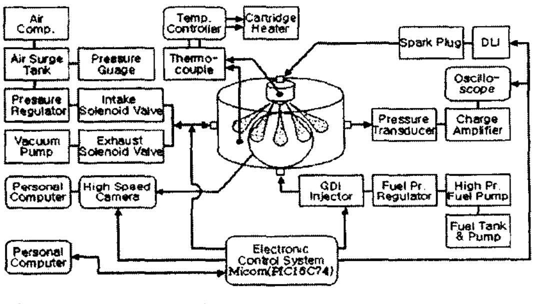


Fig. 1 Schematic diagram of experimental apparatus

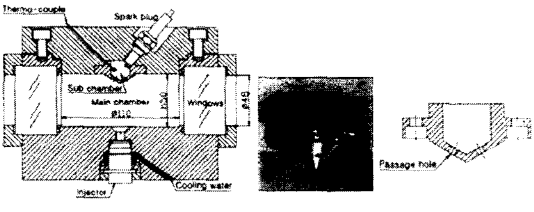


Fig. 2 Sectional view of the constant volume combustor

fuel supply system which has a regulator for constant pressure of fuel injector was used. Air was supplied to the main chamber through a filter, a surge tank, and a regulator when an inlet solenoid valve opened. Burned gases were exhausted by a vacuum pump. A DLI (Distributerless Ignition) type was used as an ignition device and ignition energy was supplied from a 12 volt battery. A series of the above processes from formation of premixture to emission of exhaust gas was carried out electronically for the accuracy and repeatability of experimental results. A micom (PIC16C74) with built-in 12 bit A/D and 8 kB EEPROM was equipped in the electronic control system, which controled an injector, solenoid valves, the DLI ignition device, and so on. The rapid pressure rise after combustion beginning in the combustion chamber was measured by a piezoelectric pressure transducer (Kistler, 6051B), transformed to electric signals, which stored in an oscilloscope after passing an amplifier (Kistler, 5011).

2.2 Experimental methods

As shown in Figure 3, volumes of sub-chamber are 2 cc, 4 cc, and 7 cc and diameters of passage holes are 1.0~2.4 mm, which is a principal factor. N-heptane and iso-octane were used as test fuels with different mixing ratio and combustion characteristics of the test fuels were examined with respect to the octane number in each condition.

Table 1 shows the experimental conditions. When internal temperature of CVC under vacuum arrives at temperature 403 K, fuel is injected 5 times for one second with equivalence ratio given in table from an injector installed at the bottom of the main chamber.

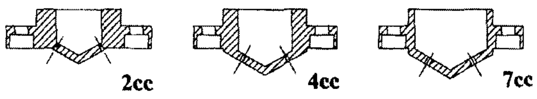
Air of 0.5 MPa in the initial pressure is inducted through an intake solenoid valve and mixed with fuel for 10 seconds. The homogeneous mixture is supplied to the sub-chamber after then. The mixture of the sub-chamber is first burned when a spark plug of the sub-chamber is discharged by an ignition signal, combustion pressure increases rapidly in the sub-chamber, and combustion products are jet through passage holes of the sub-chamber into the main chamber so that rapid bulk combustion is achieved in the main chamber.

The combustion pressure after a spark ignition is represented by an oscilloscope through a pressure transducer. When an exhaust solenoid valve opens and burned gases are exhausted by a vacuum pump, a series of experiment finishes. All these processes of experiment are controlled by an electronic control unit and are carried out in order from a start signal as shown in Figure 4.

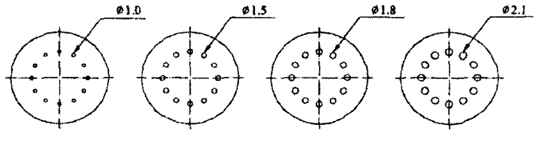
From the results of combustion experiment for each condition of the sub-chamber, it is considered that the relationship between the sub-

Table 1 Experimental conditions

Initial Pressure (P_I)		0.5 MPa
Initial Temperature (T_I)		403 K
Equivalence Ratio (ER)		0.55~1.0
Diameter of Passage Hole (D_h)		1.0~2.4 mm
Volume of Combustion Chamber	Main (V_m)	487 cc
	Sub (V_s)	2 cc, 4 cc, 7 cc



(a) Volume of sub-chamber



(b) Diameter of passage hole

Fig. 3 Schematic diagrams of sub-combustor

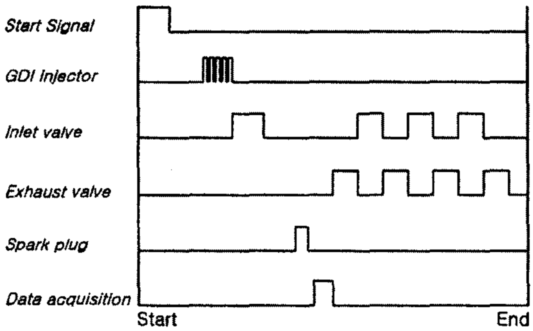


Fig. 4 Tim chart of electronic control system

Table 2 The ratio of sub-chamber volume to the passage holes volume

D_h (mm) / V_s (CC)	1.0	1.5	1.8	2.1	2.4
2	84.88	37.73	26.20	19.25	
4	169.8	75.45	52.40	38.50	
7	297.1	132.0	91.69	67.37	51.58

chamber and diameter of passage hole is important so that the relationship is represented by the ratios of sub-chamber volume to passage hole volume (which is called V_S/V_P ratio hereafter), which are shown in Table 2.

3. Experimental Results and Discussion

To examine characteristics of auto-ignition with fuel properties, experiments were carried out with fuels of various octane numbers made by mixing n-heptane and iso-octane.

Figure 5 shows variation of combustion pressure for the octane number of fuels under the conditions of ER=1.0, 0.8, where volume of the sub-chamber is 4 cc, diameter of passage hole 1.8 mm, and number of passage hole 12 (N_h=12), which are conditions optimized from the results of the previous report (Park et al., 2002). Combustion pressure in the case of spark ignition (SI method) without a sub-chamber is also shown together in the figure. In combustion by the SI method, similar combustion characteristics are shown regardless of octane number for each ER, and it is shown that combustion starting is delayed a little in the RIAI method as the octane number increases. The result means that auto-ignition and rapid combustion depend on the ignition characteristics of fuel. The characteristics were shown significantly at lean condition ER=0.8. Therefore, the RIAI method is a novel and fine method for auto-ignition and rapid combustion compared to the SI method. Especially, the RIAI method takes wide effect on lean condition.

Figure 6 shows combustion period with the V_S/V_P ratio used in the RIAI combustion method.

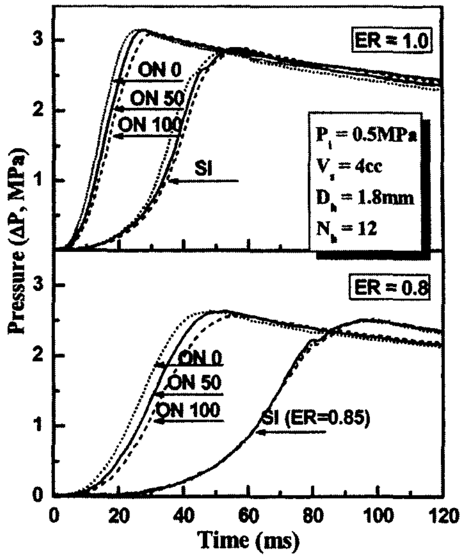


Fig. 5 Comparison of combustion characteristics for the octane number

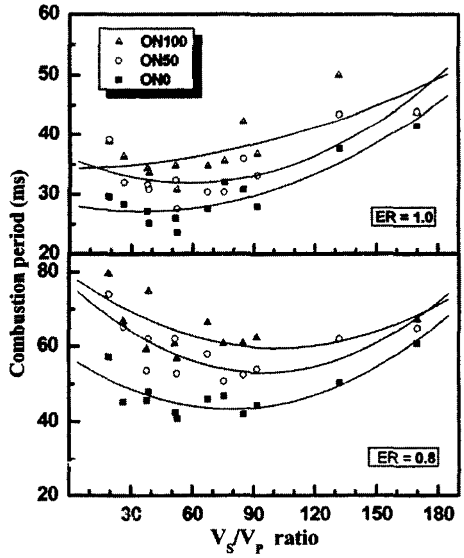


Fig. 6 Combustion period with the V_S/V_P ratio

The figure shows the results from all conditions of the sub-chamber with the octane number of fuel and at ER=1.0 and 0.8, respectively. Points which indicates the combustion period in lean condition ER=0.8 are scattered more widely than those at ER=1.0. Decrease of octane number is advantageous for rapid combustion because combustion period decreases. From rapid combustion point of view, combustion period at ER=0.8 is longer than that at ER=1.0, and the period decreases and again begins to increase nonlinearly with the V_S/V_P ratio. Especially, the V_S/V_P ratio of the sub-chamber which has optimum rapid combustion period is about 35~60 at ER=1.0 and about 50~90 at ER=0.8. It means that range of the V_S/V_P ratio increases in lean condition. Common V_S/V_P ratio realizing rapid combustion is about 50~60 in both conditions.

Figure 7 shows the maximum pressure of combustion versus the V_S/V_P ratio for octane number 0, 50, and 100 under the condition of ER=0.8 and 1.0. As the octane number of fuel is low, rapid combustion occurs well and thus the maximum pressure of combustion increases. Regardless of octane number, maximum pressure curves of the graphs in the figure show similar tendency in the maximum pressure of combustion. The maximum pressure with the V_S/V_P ratio has tendency to decrease gradually and to increases again. It is generally known that combustion period is in reverse proportion to the maximum pressure. When combustion period is quite long, the maximum pressure of combustion has a tendency to decrease. In this study, however, maximum pressure of combustion using the RIAI method depends more on the Vs/Vp ratio than on combustion period. It is shown that octane number of fuel has a few effects on the ignition delay in the RIAI combustion.

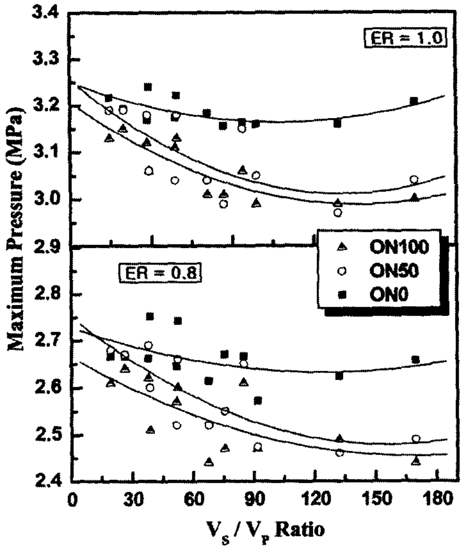


Fig. 7 Maximum pressure with the V_S/V_P ratio

Figure 8 shows the typical trace of pressure characteristics for the analysis of overall pressure. In Fig. 8, the spark starts at 0 ms, and the period from 0 ms to the occurrence of the maximum pressure is assumed to be the total combustion period (τ_{Ptotal}). The period from 0 ms to the starting point of rising pressure curve, the period from the 0ms to 10% of the maximum pressure, and the period from 10% to 90% of the maximum pressure are defined as ignition delay (τ_{ID}), early combustion period (τ_{10}), and main combustion period (τ_{10-90}), respectively, for easy expression of the time characteristics of combustion pressure.

Figure 9 shows ignition delay, total combustion period, and the maximum pressure of combustion with the octane number of fuel to compare with each case at ER=0.8. But the figure doesn't show the significant difference in ignition delay, and total combustion periods show similar tendencies to ignition delay except for the cases of ON=0 and 100 of V_S=7 cc and the case of ON=0 of V_S=4 cc. Thus, it is considered that the combustion period has no large effect on the maximum pressure of combustion.

Figure 10 shows lean limits for the octane number with the V_S/V_P ratio. The lean limits of RIAI combustion get low values as octane

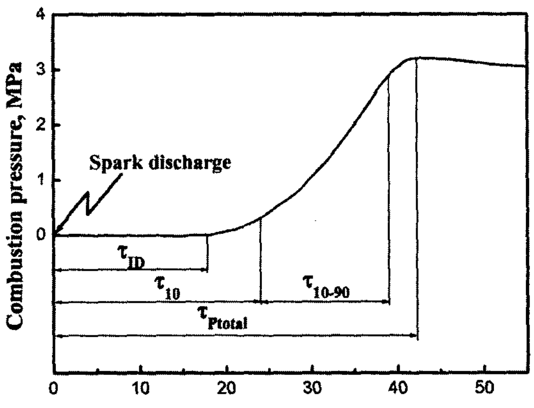


Fig. 8 Typical traces of overall pressure signal output

number decreases. The lean limits of ER are 0.65 and 0.6 at octane number 100 and 50, respectively, and the limit is expanded down to ER=0.55 at octane number zero. But, the combustion by conventional spark ignition method without a sub-chamber results in lean limit of ER=0.85 regardless of octane number.

The figure shows that the tendencies of the lean limit decrease and increase again as the V_S/V_P ratio increases and these results show similar pattern regardless of the octane number of fuel. The V_S/V_P ratio for the lowest lean limit is obtained at about 90~135 regardless of the octane number. Therefore, combustion by the RIAI method expanded lean limits by 12~35% over that of conventional SI method.

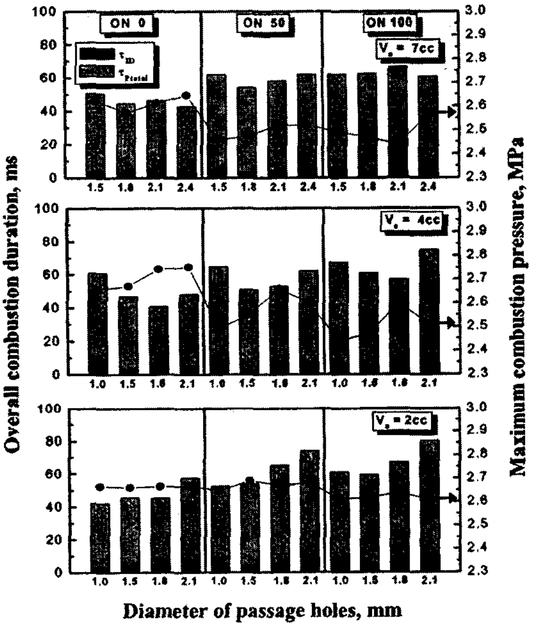


Fig. 9 Combustion period and maximum pressure with diameter of passage hole

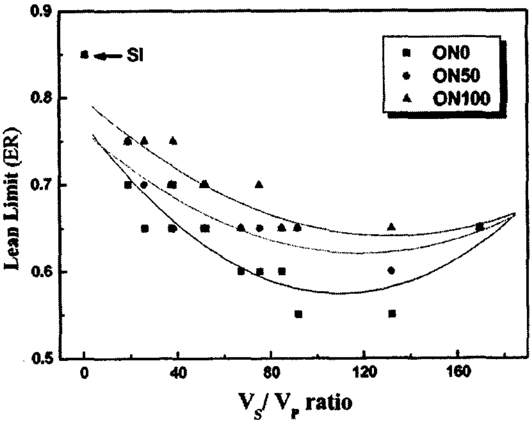


Fig. 10 Lean limit with the V_S/V_P ratio

4. Conclusions

(1) The conventional SI method shows similar combustion characteristics without regard to the octane number of fuel and the RIAI method realizes rapid bulk combustion as the octane number is low, that is, as ignition properties is good. The effect is larger and larger in lean combustion.

(2) In a condition of ER=1.0, the most rapid combustion occurred in the V_S/V_P ratio of about 35~60 and of about 50~90 for lean combustion ER=0.8. Therefore, the V_S/V_P ratio should be increased for lean conditions.

(3) For combustion using the RIAI method, the maximum combustion pressure increased when the octane number of fuel is low. It is considered that the maximum combustion pressure is high because of rapid bulk combustion by auto-ignition.

(4) The lean limit is further expanded by the RIAI combustion as octane number gets low, and the RIAI method expands combustible range by 12~35% over that of the SI method.

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